The impacts of project scale, scope and risk allocation on financial returns for clients and contractors in Energy Performance Contracts - a stochastic modelling analysis

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I, Pamela J Fennell, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the work.

Abstract

With a projected annual value of £1bn, the UK energy performance contracting market has the potential to unlock a large number of energy efficiency projects by reducing risk of investing in energy efficiency upgrades in industry applications and in buildings. However, market development to date has been slow and little analysis has been undertaken to understand the characteristics of successful projects. A better understanding of the impact of project scale, scope and risk allocation on outcomes for building owners and their contracting partners, known as Energy Service Companies (ESCOs), would enable investment programmes to be targeted more effectively.

This study uses probabilistic energy modelling of hypothetical case studies in the UK schools sector to assess the scale of possible energy savings from a range of retrofit measures. Samples from these distributions of energy savings are used as inputs to an economic model which allows the impact of different approaches to measurement and verification of the energy savings to be explored, along with the impact of energy price assumptions, project scale and scope and different guarantee mechanisms.

The case study projects are based on hypothetical school buildings and combine 3 different scales of project with 2 different groups of retrofit measures.

Despite evidence from previous work that transaction costs are critical to financial outcomes of projects there is an absence of data on the scale of transaction costs in the current literature. This study uses semi-structured interviews with building owners and ESCOs to elicit transaction cost information for the case study projects which form another set of inputs to the economic model.

Global sensitivity analysis is used to screen for non-influential parameters in the energy model (modified Morris method), enabling a significant reduction in computational burden. Global sensitivity analysis is also used with the economic model to rank inputs in order of their influence on financial outcomes for clients and ESCOs, providing insight into the areas of uncertainty which have the largest impact.

The results of this study suggest that

- not all of these projects are well-suited to this form of procurement. In particular, cases with a small number of energy conservation measures perform less well than those with a more diverse set of measures
- more effective monitoring methods are needed, but crucially, these must be focused on the collection of data which facilitates the allocation of responsibilities between the parties.
- steps to increase market competition must take an holistic view of transaction costs to avoid reducing market testing of costs in competition which will result in increasing policing and enforcement costs
- bundling smaller projects together cannot reduce risks for the ESCO unless there is a mechanism for balancing returns between individual projects.

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Peer-reviewed journal papers

- Pamela J Fennell, Paul A Ruyssevelt, and Andrew ZP Smith. Financial viability of school retrofit projects for clients and ESCO. *Building Research & Information*, March 2016

Peer-reviewed conference papers

- Pamela J Fennell, Paul A Ruyssevelt, and Andrew ZP Smith. Energy Performance Contracting; is it time to check the small print? In *Proceedings of the 4th European Conference on Behaviour and Energy Efficiency*. Coimbra, Portugal, September 2016

- Pamela J Fennell, Paul A Ruyssevelt, and Andrew ZP Smith. Exploring the Commercial Implications of Measurement and Verification Choices in Energy Performance Contracting Using Stochastic Building Simulation. In Charles S Barnaby and Michael Wetter, editors, *Proceedings of the 2017 IPBSA Building Simulation Conference*. San Francisco, USA, September 2017

List of abbreviations used in this thesis

BEIS	UK Government Department for Business, Energy and Industrial Strategy
BES	Building Energy Simulation
CDF	Cumulative Density Function
CEF	Carbon and Energy Fund
DfE	UK Government Department for Education
DEC	Display Energy Certificate
DECC	UK Government Department for Energy and Climate Change (responsibilities subsumed into BEIS)
DMA	Direct Measurement Approach
DSCF	Discounted Cash Flow Model
ECM	Energy Conservation Measure
EE	Elementary Effect
EERE	US Office for Energy Efficiency and Renewable Energy
EPC	Energy Performance Contract
ESCO	Energy Services Company
FE	Forms of Entry
IGP	Investment Grade Proposals
IMA	Indirect Measurement Approach
IMPVP	International Performance Measurement and Verification Protocol
JCT	Joint Contracts Tribunal
KS	Kolmogorov-Smirnoff test
M&V	Measurement and Verification
NDEE	Non-Domestic Energy Efficiency
NPV	Net Present Value
PAT	Principal-Agent Theory
PPFs	Public Procurement Frameworks
PRT	Property Rights Theory
RPI	Retail Price Index
TCE	Transaction Cost Economics

Chapter 1

Introductory Material

1.1 Motivation for this thesis

The UK government's Climate Change Act passed into law in 2008 [5]. The Climate Change Act was the first example of a country introducing a long-term, legally binding framework to reduce carbon emissions in response to the growing threat of climate change. The act underlined the important role of efficient use of energy resources in reducing UK carbon emissions. However, despite continuing acknowledgement that energy efficiency is "fundamental to decarbonising the UK, maintaining secure energy supplies, and increasing the productivity of [...] businesses" [6] investment in energy efficiency projects in the UK has been very limited to date and the energy intensity of non-domestic buildings has been static since 2007 according to a 2015 Committee on Climate Change report [7]. The UK is by no means unique in this respect with similar concerns reported in a wide range of jurisdictions [8, 9, 10, 11]. This lack of investment in energy efficiency has been termed the "energy efficiency paradox": technologically orientated analysts see a divergence from the optimal diffusion rate of energy-efficient technology as evidence of market barriers and thus argue for policies to promote investment and overcome these barriers [12]. O'Malley et al. [13] defined barriers to energy efficiency as "postulated mechanisms that inhibit investment in technologies that are both energy efficient and economically efficient". However, other researchers have argued that energy markets are generally efficient and that lower than expected levels of investment are explained by the economic rationality of consumers, particularly with reference to prospect theory which suggests that uncertain long-term returns from the investment would be weighted unfavourably in comparison with certain sunk costs [14]. This is likely to be compounded by consumer scepticism of economic predictions since studies of technological potential are generally undertaken by authors with some bias and tend to underestimate costs and overestimate benefits [15].

Many advocates have proposed a form of contract where the installer of an energy efficiency measure guarantees the level of resulting energy savings, suggesting that this approach would unlock investment in energy efficiency measures by de-risking the savings associated with them. This type of arrangement, termed an Energy Performance Contract (EPC), has been actively pursued in the United States since the late 1970's [16] and was mandated by the European Parliament in 2006 [17].

By 2010, the UK EPC market was estimated to be worth \$530m per annum [18], and later studies suggest that the market has continued to grow [19], particularly in public sector facilities such as schools and hospitals where typical projects have involved installation of a range of energy efficiency measures including lighting upgrades and heating controls [20]. Installation of Combined Heat and Power plants has been a key feature of EPC project in the health sector [19]. However, the UK Committee on Climate Change's concerns about the slow pace of uptake of energy efficiency improvements [7] were published nearly a decade after the EU directive, so it seems clear that while EPCs have been gathering some momentum in the UK, they have not had the transformational effect that was hoped for. Nonetheless, EPCs are a significant procurement route in the UK. The Greater London Authority's RE:FIT programme has seen over £100 million of capital investment delivered in energy efficiency over 7 years for over 200 public sector clients [21]. It is clear that clients are routinely developing projects for procurement, and making potentially critical decisions about their composition despite a lack of evidence in the literature for the impact those procurement choices may have on project outcomes. As the result, the aim of this study is to explore some of those procurement choices to understand their impact. By understanding better which projects are more likely to be successful, future procurement can be better targeted.

1.2 Structure of this thesis

This thesis is structured as follows: Chapter 2 begins by establishing a definition for Energy Performance Contracts which is used as the basis for a review of the existing literature on EPCs. It is clear from the literature that transaction costs and uncertainties around energy price and energy savings are critical to the success of energy performance contracts. This review also highlighted the need for an underpinning theoretical framework.

Sorrell [22] proposed Transaction Cost Economics as a theoretical framework for understanding EPCs. Chapter 3 discusses the appropriateness of this framework and how it can be extended to incorporate uncertainty. Based on this, four research hypotheses are derived from Sorrell's [23] work which form the basis of the work undertaken in this study.

Chapter 4 sets out the context in which the research hypotheses are explored, the modelling strategy is introduced and the data collection approach for the first of the two principal elements of the analysis, transaction costs, is detailed.

The second principal element of analysis is production cost savings; in this context, energy cost savings. Chapter 5 begins by identifying the project dimensions which must be defined in order to test the research hypotheses and explains the approach to using Building Energy Simulation (BES) modelling to determine energy savings. A key focus of this chapter is the treatment of uncertainty in BES models and the use of parameter screening to reduce model dimensionality.

Chapter 6 begins by presenting the transaction cost data collected through interviews with a range of Clients and Energy Service Companies (ESCOs). The challenges and limitations of the data are discussed and evidence for the impact of market competitiveness on financial returns is considered.

Chapter 7 explores the impact of different approaches to measurement and verification (M&V) of energy savings. The different balances of risk transfer under each option are discussed. The BES results for alternative M&V approaches for two different sets of Energy Conservation Measures (ECMs) are presented and a global sensitivity analysis is undertaken to identify the impact of M&V strategy on financial outcomes for Clients and ESCOs.

Chapter 8 draws the transaction cost results of Chapter 6 and the production cost results of Chapter 7 together to explore the impact of project scale (number of buildings) and project scope (number of ECMs installed in each building) on financial outcomes for Clients and ESCOs.

Chapter 9 concludes this thesis by summarising the results of Chapters 6, 7 and 8 and setting out the implications for procurement decisions that are highlighted by these results. The limitations of this study are discussed and suggestions are made for further work.

Chapter 2

Literature Review

2.1 Overview

This chapter begins by considering the origins of energy performance contracting (EPC) and defining which activities are encompassed by the term. This definition is used as the basis for a review of the existing literature on EPCs which resulted in a large number of articles for review. The most highly cited of these articles (measured by total number of citations) are reviewed to develop an understanding of the aspects of EPCs which have received the bulk of research attention to date. A key theme in the literature reviewed was the exploration of barriers to development of EPCs around the world. A number of common suggested barriers were identified. Understanding two of these proposed barriers: risk/uncertainty and transaction costs required a finer grained approach to the subject than was generally available in the most highly cited articles which largely took a theoretical or explanatory approach to the subject. To address this, the scope of the literature review was expanded to include any literature dedicated to these two elements of EPCs and less highly cited papers were included in the search. Gaps in the literature were identified as a result, in particular, as identified by Sorrell [22], the need for an underpinning theoretical framework. The proposed theoretical framework is the subject of the following chapter.

2.2 Defining Energy Performance Contracting

Whether EPC should be viewed as heralding the shift from the industrialised economy to a performance based economy as suggested by Steinberger [24] or more prosaically as a mechanism for unlocking energy efficiency investments, it has received considerable attention as part of a suite of solutions to deliver significant and rapid reductions in carbon dioxide emissions to address climate change goals [25, 26, 27]. EPC has its modern origins in the US as a response to the oil shocks of the 1970s [28]. Goldman et al. undertook the first comprehensive survey of Energy Service Company (ESCO) activities in the US in 2002 noting that ESCOs were "increasingly moving away from performance contracting". As a result, the term ESCO covers an expanding range of activities and it is necessary to clarify the scope of activities which is of interest for this study. Duplessis et al. [29] illustrated this expansion as shown in figure 2.2.1

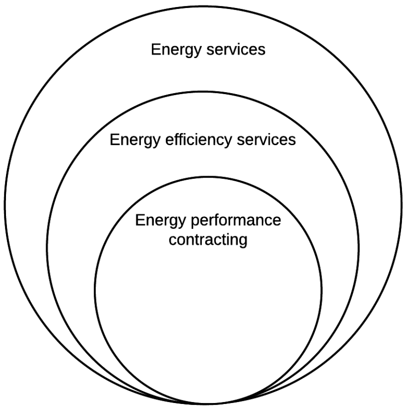

Figure 2.2.1: Expanding scope of ESCO activities

In line with Duplessis et al. [29], the definition of Energy Performance Contract used in this study is taken from EU directive 2006/32/EC: "A contractual arrangement between the beneficiary and the provider (...) of an energy improvement measure, where investments in that measure are paid for in relation to a contractually agreed level of energy efficiency improvement."[17, article 3j].

An initial scoping review of the literature was supplemented with a systematic review based on citation counts to ensure that there were no gaps in the material surveyed. Literature relating to Energy Performance Contracting was identified from the Scopus database for journal articles published between 2005 and 2017, using the following search terms:

- "energy performance contract"
- "energy services company"
- "energy services companies"

The terms 'ESCO' and 'EPC' were not used in the search as these abbreviations were found to be used in various unrelated fields. A total of 377 papers were identified and the 100 most cited (by total number of citations) were selected for inclusion in the review. Paper abstracts were then reviewed to ensure that only papers which referred to Energy Performance Contracting as defined above were included. This resulted in 67 papers for review. More detailed review of the full text of the remaining 67 articles and book chapters identified a further 15 references which did not directly relate to energy performance contracting and these were also removed. Four references were excluded; of these two items were excluded as only the abstract was in English, access was not available to one item and one item had been withdrawn. This resulted in a total of 48 references for review.

2.3 Energy Performance Contract markets

Much of the literature surveyed seeks to present the current state of energy performance contracting and ESCO activities, and identify the actual and potential scale of markets around the world. These efforts are complicated by the broad scope of ESCO activities, which adds to the difficulty of determining the market size. Goldman et al.'s [28] original market review in the US calculated market size by determining the turnover of ESCOs for whom energy performance contracting was at the core of their business. Revenues for non-respondent ESCOs were estimated using a delphi process. This procedure was repeated in 2008 and in 2013 by which time the US market was estimated to have grown from $2bn in 2002 to $6bn in 2013. Data for the size of other markets is more difficult to determine. Marino et al.[18] estimated the UK ESCO market at $530m in 2010 based on expert interviews. Nolden and Sorrell [19] report that the market had grown considerably by 2014 but do not provide a figure for the market size. The Japanese performance contracting market was worth $250m in 2005 [30] and Yuan et al. [31] report the Chinese market size as $16bn in 2014 although Kostka and Shin [32] caution that "many companies registered as ESCOs are simply taking advantage of finance and tax breaks designed to promote the development of the industry and are not engaged in EPCs" suggesting that this figure may be an over-estimate. Despite the difficulties of assessing market size it is clear that the global market for energy performance contracts is substantial and that most commentators agree that there is considerable potential for additional growth.

2.3.1 Barriers to market development

Although the market for Energy Performance Contracts is large and growing and energy performance contracts offer some demonstrable benefits, many commentators have identified barriers which may prevent it reaching its full potential [33, 34, 35, 18, 36, for example]. Reasons for this apparent lag and/or proposals for supporting market growth are explicitly addressed in a large proportion of the literature; in all 24 unique accounts were found and a number of recurring themes were identified:

1. Awareness and incentives to invest

   For an Energy Performance Contract to be a possibility there must first be a desire to improve energy efficiency and an awareness of the potential solution offered by an EPC. Hansen [33] suggests there is a global lack of awareness, a view borne out by the range of commentators sharing it. Commenting on the EU ESCO market, Bertoldi et al. [34] report a lack of awareness or understanding on the part of potential clients in some member states of the importance of energy efficiency or of how EPCs could be used to increase it. This finding is mirrored in analyses of the Swedish market by Soroye and Nilsson [37] and in Pätäri and Sinkonen's [38] and Suhonen and Okkonen's [39] analyses of the Finnish market. Similar concerns are raised by Jensen et al. [40] reporting on ESCOs in Danish municipalities and Aasen et al. [41] in a recent review in Norway. However, such a concern is not restricted to the northern european market with Kostka and Shin [32] noting the low sophistication of clients as a concern in China. This is echoed by Painuly's [42] report on lessons learned from pilot projects in India, Brazil and China and Okay et al.'s [43, 27] review of and update on the emerging Turkish market. Nolden and Sorrell [19] note that even in jurisdictions where awareness of the need for energy efficiency might be expected to be high, energy efficiency investments must compete for scarce capital resources.

2. Cultural barriers

   The need to adapt to local market and cultural norms is discussed by many authors [44, 37, 25, 45, 46]. Yuan et al. [31] note that even within a single country, in this case China, there is a need to take account of regional differences. Some cultural barriers are particularly challenging to market development: for example the absence of a risk capital market and experience in Turkey [43] or a moral objection to a third party profiting from public sector actions in some Nordic countries [38, 39, 40].

3. Government support

   Development of Energy Performance Contract markets relies on government action in three key guises: Firstly for the establishment of the appropriate legal and regulatory framework which allows energy performance contracts to be undertaken [47, 33, 37]. The need for legislative change to financial markets in Turkey to allow access to risk capital is a good example of this [43]. Secondly, governments can influence market activity through the availability of subsidies for energy efficiency investments [45] or tax incentives [48]. Thirdly, governments also have an important role to play as clients, leading by example [34].

4. Access to finance

   Access to finance is cited by many authors as a potential barrier to market development [34, 18, 49, 50, 43, 51] although the importance of this barrier appears to vary depending on the market in question. Nolden and Sorrell [19] note that "Few of [their] interviewees identified financing as a major obstacle" when considering the UK market.

5. Transaction costs

   High transaction costs are identified by a wide range of authors as a barrier to market expansion in locations as diverse as China, Finland, India and Denmark [32, 39, 42, 40]. These findings echo Sorrell's [22] earlier conclusions that transaction costs would be a determining factor in deciding governance structures for procuring energy efficiency projects. However, in all cases these are theoretical or qualitative conclusions and none of the studies reviewed presented a quantitative analysis of the economics of energy performance contracts.

6. Uncertainty

   Risk and uncertainty are highlighted by a large number of authors as barriers to market development. Backlung and Eidenskog [51] and Suhonen and Okkonen [39], Marino et al. [18], Mills et al. [35] and Vine [47] all expressly discuss the potential for actual savings and hence financial returns to vary from the expected values. Standardisation of contracts and measurement and verification procedures is seen as a key strategy for addressing these risks [47, 34, 52, 48]. A separate aspect of uncertainty relates to the long-term nature of the contracts, with Nolden and Sorrell [19], Pätäri and Sinkonen [38] and Jensen et al.[40] all highlighting the potential unwillingness of clients to enter into long term contracts which might either restrict their ability to respond to future business demands or realise much lower than anticipated returns due to changes in estates strategies.

By using ranking according to number of citations, the literature surveyed has potentially been biased towards theoretical and descriptive articles with an emphasis on attempts to “understand the model” [38] and discussion of theoretical dimensions of energy performance contracts. This focus seems appropriate for the first four barriers identified which are expected to be features of the market context in which an EPC project is undertaken. For the final two however, a significant degree of heterogeneity might be expected within a market and so the original literature search was extended to explore the dimensions of ‘transaction costs’ and ‘risk/uncertainty’ in more detail. This was done by relaxing the ranking requirement and including either of the terms “transaction costs” or “ risk” in the original search. The addition of the term “transaction costs” resulted in the identification of an additional four studies. Including the term “risk” resulted in the addition of 31 articles. Relaxing the ranking criterion meant that less heavily cited studies were included. In many cases the lack of citations is likely to be due to the relative recentness of the articles, the oldest of which dated from 2014. In some cases; however, the level of citations may result from lack of access to the article and it was necessary to exclude a further 9 articles due to a lack of access. Review of the abstracts resulted in the identification of a further 3 articles which did not relate to energy performance contracting as defined in section 2.2 above. A previous study by Fennell et al. [2] which formed a pilot study for the current work has been excluded from this review.

2.3.2 Risks and uncertainties in Energy Performance Contracts

The pool of references developed from the combination of the original and the extended literature searches can be thematically divided into four main categories: studies which use expert opinion to identify risks [53, 54], case studies which include discussion of risks in particular contexts [55, 56, 57, 58, 59, 60], consideration of risk allocation as a result of sharing mechanisms typically modelled using game theory approaches [61, 62, 63, 64, 65], and discussions of the implications of measurement and verification strategy [66, 67].

The risk identification studies [53, 54] analysed described two key sources of risk and uncertainty which were also explicitly identified in a number of case study examples: the variability of energy savings, and the uncertainty around energy prices. Mills et al. [35] suggested a list of possible causes for these uncertainties:

- "Inadequate time or methodology to establish an accurate volumetric consumption baseline
- Inability to monitor behavioural changes that could result in greater consumption of energy when new equipment is installed
- Inability to monitor and mitigate actions that could decrease asset efficiency, such as poor maintenance
- Volatility in future energy rates, currency exchange rates, interest rates, etc."

They concluded that "Quantitative risk analysis is essential to correctly value energy-efficiency projects in the context of investment decision-making" [35, p. 198].

Game theory has been used to explore optimum design of risk sharing mechanisms between clients and ESCOs by a number of authors [61, 62, 63, 64, 65, 68, 69]. Most of these studies can be considered to be exploratory applications of game theory, since they are based on a bi-partite interaction between a client and a single ESCO rather than a competitive bidding situation which would be more likely in practice.

2.3.2.1 EPC risks in context

While a number of the case studies identified did not explicitly evaluate risks and provided more general explorations of particular projects [55, 59, 60, 70, 71, 72, 73, for example], others provided a more detailed consideration of how risk and uncertainty can be approached as set out in table 2.3.1.

Table 2.3.1: Treatment of risk and uncertainty

Paper	**Approach**
Deng et al. [56]	Uncertainty is explicitly considered in developing a model for determining expected energy savings under uncertainty using stochastic processes to model energy prices and savings to determine the optimum level of guarantee that should be offered by the ESCO. Data from real projects at the University of Maryland are used to demonstrate the model. *Limitations:* Variation in possible energy savings is treated in broad terms with values for the percentage volatility of energy prices of $\sigma = 1\%$, $\sigma = 10\%$ and $\sigma = 25\%$ used to estimate the potential variation in energy savings from the estimated value. The stochastic process used to calculate energy savings results in a volatile profile for energy savings over the life of the project and the potential for significant spikes in energy consumption figures in later years. This is at odds with the picture presented by other authors, e.g. Berghorn and Syall [54] who find that "the most important risks were found to occur during the earliest project phases" and standard industry practices reported by Shonder and Avina [66] who report that variation in energy consumption in later years of the project is more likely to be caused by changes in the client's energy consumption patterns and that ESCOs were seeking to restrict measurement and verification of energy savings to a one-time test at completion of installation to address this. The study treats energy savings and penalties as the only contributions to cost and does not include installation or transaction costs in the analysis.

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Paper	Approach
Heo et al. [74]	Uncertainty about existing building condition is explicitly considered. The approach uses parameter screening followed by bayesian calibration of a normative energy model to create a computationally light-weight model which could be used to assess different energy conservation measures. The model is tested on a university building in Cambridge, UK. *Limitations:* The ranking is based on a fixed price for gas and a simple payback calculation which ignores the other key source of uncertainty identified in section 2.3.2.

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Paper	Approach
Lee et al. [57]	Probabilistic analysis of a chiller replacement project for a commercial building in Hong Kong, building on elements of Heo et al.'s approach and extending the consideration of uncertainty to include variations in weather and system degradation over time. *Limitations:* The methods used are relatively computationally intensive with 10,000 model runs required for pre and post-retrofit conditions. Model dimensionality could be reduced by application of the parameter screening step proposed by Heo et al. to create a reduced model. The approach to generating variations in weather files is also subjective, for example, wind speed appears not to be treated as a variable parameter although it might be expected to have some impact on chiller operation due to the effect of windspeed on infiltration. In common with Heo et al.'s work [74], while the methods proposed represent a significantly greater degree of rigour in the treatment of uncertainty, the underlying analysis is not EPC specific and is not dependent on the contractual arrangements for the energy efficiency investment in question.
Bustos et al. [58]	Energy model is coupled with a business model to consider the case of a roof-top solar photo voltaic system in Santiago, Chile. In their approach, the net present values of client and ESCO returns are considered separately to determine the optimum sizing of the system and sensitivity analysis is used to identify the most influential parameters. *Limitations:* Details of the procedures used are ill-defined.

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Paper	Approach
Wang et al. [63]	The lack of rigorous quantification methods for investment decisions is criticised as likely to lead to a lack of understanding of their volatilities. It is highlighted that this is likely to lead to conservative contract clauses as the ESCO seeks to avoid payouts due to savings shortfalls. The study is based on a game theoretic model of normative decision making where client and ESCO expected utilities are adjusted by their risk tolerance. A full probabilistic simulation of energy savings is undertaken. *Limitations:* This approach does not take account of the implications of opportunism and rent seeking behaviour proposed in transaction cost economics [75], the sunk costs incurred by client in undertaking a procurement process would leave the client vulnerable to hold-up costs and could be expected to counter their natural risk tolerance levels. How risk tolerances would be manifested in real procurement situations is unclear, particularly for the UK context where procurement decisions are open to challenge and subject to scrutiny, meaning evaluation criteria would normally be set out in advance.
Bannai et al. [30]	Data from 4 industrial co-generation projects was used to explore the use of fuel derivatives to hedge against fuel price uncertainty. *Limitations:* It is not clear if this can be generalised beyond co-generation or what transaction cost implications might be.
Concluded	

Some suggestions for best practice for the treatment of risk and uncertainty can be drawn from table 2.3.1:

- probabilistic simulation of energy savings using building energy simulation is important and the computational load can be reduced through the application of parameter screening
- probabilistic simulation of energy price volatility is also required
- variability of the performance of energy conservation measures over time should be considered, although the technique proposed in Deng et al. is not appropriate
- variation in weather over time should also be considered, although as noted by Kalamees et al. [76] a number of climatic variables affect heating and cooling consumption.

2.3.2.2 The significance of measurement and verification in risk allocation

Many commentators identify standardised Measurement & Verification (M&V) processes as a key market enabler (or, its absence as a key market barrier). Only two references were found which take a slightly different view, with Jensen et al. [40] placing a higher emphasis on trust in the context of Danish municipalities and Sarkar and Singh [77] cautioning against over-complex M&V arrangements as a potential market barrier in developing countries. In contrast, a variety of US based studies quoted in Kats et al. [78] provide evidence of greater savings in projects with robust M&V arrangements.

The most commonly used approach for measuring and verifying savings is the International Performance Measurement and Verification Protocol (IPMVP) which grew out the US EPC industry standards, [79] with ten Donkelaar et al. [80] reporting its use in just under 50% of 100 European projects surveyed. However, as Ginestet and Marchio [81] point out: "[t]he general principles of the method quoted in the IPMVP documents [...] remain imprecise, they only lead to the parameters identification but do not allow the immediate realisation of calculations."

Shonder and Avina [66] highlight the potential for different measurement and verification approaches to result in different risk allocations for clients and ESCOs and different values for measured savings as a result. This difference in measured energy savings between the different IPMVP options is also reported by Ginestet and Marchio [81] and Wang et al. [63].

2.3.3 Transaction costs in energy performance contracts

Although transaction costs were identified as important barriers to market development, they receive relatively little attention in the literature. Polzin et al. [82, p. 135] draw on Sorrell [22] to define transaction costs in the energy performance contract context as costs which are "incurred within organisations through managing and monitoring personnel, procuring inputs and capital investment, and 'the costs associated with organising ('governing') the provision of [...] streams and/or services' [22]. When the same streams and/or services are sourced from an external provider, transaction costs are associated with source selection, contract management and performance monitoring, dispute resolution and opportunistic behaviour." Polzin et al. was the only study reviewed thus far in this chapter to explicitly consider transaction costs. Although "investment" or "implementation" costs were mentioned in several of the case studies [55, 58, 59, 60], it is not clear that they include any additional costs beyond those of installation. This is significant since as Pätäri et al. [83, p. 1452] note, in practice transaction costs can have a fundamental impact on the financial viability of projects, highlighting that "[t]he main argument against too small projects was that the administrative and other transaction costs will not be offset by the benefits". This conclusion is echoed by Schubert et al. [84, p. 175] who similarly note that "a specific problem in the context of environmental finance and associated transaction costs is investments of the smallest scale [...]. In such cases, it is likely that the costs of negotiating the financing terms exceed the gains from the project. Such transaction costs can, again, only be lowered through a bundling of smallest-scale projects".

In common with Polzin et al.'s [82] use of a transaction cost economics

(TCE) framework to analyse German municipal street-lighting projects, Yang et al. [85] use TCE to explore energy management services in Taiwan. Both studies use an indirect approach [75] to assess the impact of project characteristics on transaction costs and hence the viability of the proposed project.

2.4 Summary

The size of the market and the existence of concerns about its rate of development suggest that the Energy Performance Contract market deserves further exploration. However, much of the existing literature is largely descriptive, focused on the current state of markets worldwide, and as highlighted by Sorrell [22], lacks an underpinning framework which would provide clear directions for research. Nonetheless, it is clear from this literature that transaction costs and uncertainties around energy price and energy savings are critical to the success of energy performance contracting projects and hence markets. However, despite this importance, no studies were found which combine a rigorous assessment of project and price uncertainties and which take into account the potentially very significant role of transaction costs.

To address the methodological shortcomings he identified in the field, Sorrell proposed Transaction Cost Economics as an appropriate framework for analysis. The following chapter explores this framework in more detail and considers how it could be applied to energy performance contracting projects and extended to encompass the uncertainties inherent in these projects.

Chapter 3

Theoretical Framework

3.1 Overview

Sorrell [22] first set out the need for an underpinning framework to guide research into energy performance contracts. While the literature surveyed in Chapter 2 gave a broad overview of the subject, the focus on market level phenomena resulted in a relative lack of explanatory work at the level of individual projects. Although little work has been done at an individual project level, large capital sums are being invested through EPCs [21] and clients are routinely defining projects for procurement without a strong evidence base for the impact of those decisions. Decisions about project scale, scope and risk transfer are made for each project without the benefit of a strong evidence base for guidance.

Sorrell [22] highlighted the benefits of using a clear theoretical framework to underpin exploration of EPCs, arguing that a more systematic approach would be likely to uncover greater insights. The purpose of the theoretical framework in this study is to allow a theoretical survey of the topic to highlight areas for exploration rather than to provide an analytical framework. Sorrell proposed Transaction Cost Economics (TCE) as a suitable framework to underpin this work. This chapter begins with a consideration of alternative models which could be used to explore EPCs and after confirming that TCE is the most appropriate model provides a brief description of the framework and how it can be applied in the context of energy performance contracts. The most appropriate form of analysis is considered and the nature of uncertainty is considered. This chapter concludes by setting out the research hypotheses which emerge from the TCE approach and which form the basis of the work undertaken in this study.

3.2 Alternative approaches to exploring contractual relationships

Tadelis and Williamson [86, p. 159] frame the move away from the neo-classical focus on the laws of supply and demand as a shift in perspective from the "lens of choice" to the "lens of contract". The shift from consideration of market exchange where price is the key consideration to one of market structure is important in the context of continuing exchange relationships and particularly relevant in the context of energy efficiency. Energy use has traditionally been approached from a supply perspective with many decades worth of government policy focused on supply arrangements [87]. The demand-side perspective has emerged more recently and focuses on the services provided as a result of energy use (e.g. lighting, heating etc.) as illustrated by Hannon et al. [88] drawing on the work of Sorrell [22] and shown in figure 3.2.1. The delivery of energy services is framed as a spectrum, ranging from a traditional approach on the left of the diagram, where the building owner purchases energy from a utility provider and owns the equipment to convert the supplied energy into the required service, for example, lighting or heat. At the other end of the spectrum, a building owner might purchase an energy service from a provider who owns the conversion equipment (lighting infrastructure, heating infrastructure etc.)

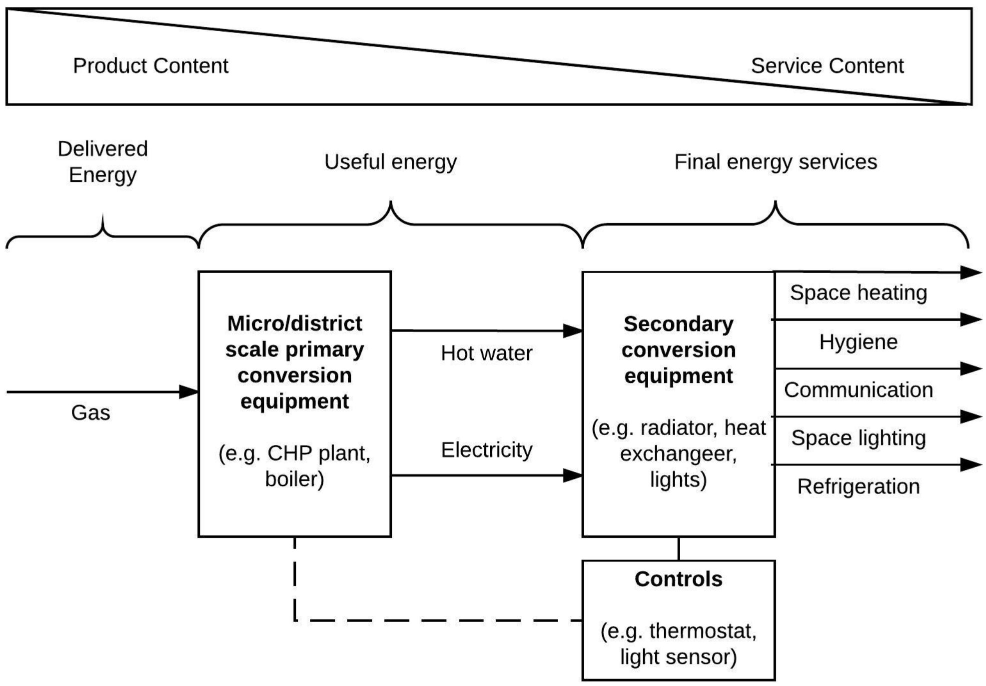

Figure 3.2.1: Energy supply or energy demand

As illustrated in figure 3.2.1 conversion of an energy supply into an energy service can be viewed as a transaction which can be delivered through alternative governance structures which can be framed as the 'make' or 'buy' options:

- an in-house arrangement in which a building owner enters into a supply contract with a utility provider and retains responsibility for the conversion of the supplied energy into the desired services (e.g. heating, lighting etc.) using their own equipment (e.g. boilers, lamps etc.) - the 'make' option.

- an outsourced arrangement in which a building owner enters into a contract for the provision of the final energy service with a specialist provider who may have ownership of the conversion equipment (e.g. boilers, lamps etc.) - the 'buy' option.

Ronald Coase first proposed that the transaction should be treated as the critical unit of analysis, receiving a Noble prize for economics for his early work on the subject [89]. Coase [90] called for a "comparative systems approach" which explicitly attempts to ascertain the economic consequences of alternative ways of organising the allocation of resources [91]. In this approach, a transaction is defined as occurring "when a good or service is transferred across a technologically separable interface" [92].

Three alternative models have been proposed as frameworks for understanding transactions: Transaction Cost Economics (TCE), Property Rights Theory (PRT) and Principal-Agent Theory (PAT). Each of these frameworks aims to address a key shortcoming of the neo-classical approach, in which "[t]he firm is treated as a perfectly efficient 'black box', inside which everything operates perfectly smoothly and everybody does what they are told" [93], PAT [94] recognises the potential for conflicts of interests between parties within an organisation or between organisations and has been used to explore optimal incentive structures for many different problem settings. However, PAT does not consider the bounds of the firm and is thus silent on the 'make or buy' question at the heart of this study.

Transaction Cost Economics was developed from Coase's original ideas by Williams [95, 96] and is based on the concept that no contract can be complete since not all circumstances and behaviours can be foreseen when it is written, not all actions can be observed and verified, and even if this were all possible it would be prohibitively expensive to write a contract so all encompassing. In the absence of complete contracts, contracting incurs costs, and parties to a contract can be subject to hold-up problems when circumstances arise that can be exploited by one party or another. Asset specificity is a key issue in TCE since if assets have equal value in alternative uses, the potential for opportunism and haggling is reduced.

Hart criticised TCE for failing to explain why haggling and hold-up costs are reduced within a firm [93] and developed Property Rights Theory as an alternative model. PRT is also concerned with how the non-contractible issues are resolved. Ownership of assets is the key to this according to PRT: "ownership is a source of power when contracts are incomplete" [97]. The model provides a tool for understanding the structure of markets and addressing the 'make or buy' question concluding that "a party with an important investment or important human capital should have ownership rights" [97].

Although it has been suggested that PRT allows a more refined approach to understanding how asset specificity drives the choice of governance structure than TCE [98], PRT is based on two assumptions that do not fit well with the current study:

- symmetry of information [99]. This is unlikely to be valid; since the ESCO is responsible for designing and installing ECMs it seems clear that the ESCO will have more information about ECM performance and likely energy savings than the client, and conversely, the client will have information about the way the building is used which will not be available to the ESCO.

- the costs of contracting do not differ between the in-house and the outsourced solution [99]. In the UK context where a competitive procurement is necessary for a public sector client to comply with their fiduciary responsibilities, it is difficult to support this assumption. Although Hart argued in later work that there was no reason why competition could not occur internally to the client organisation [100], this competitive market does not currently exist.

Since these assumptions are believed to be invalid in the UK public sector context, the TCE framework which does not rely on these assumptions was preferred to the PRT framework for this study. The validity of this choice is examined in Chapter 6.

3.3 The Transaction cost economics framework

The transaction cost approach is based on two behavioural assumptions:

1. bounded rationality - individuals intend to be rational but experience limits in formulating and solving complex problems and in processing information. Given bounded rationality it is impossible to deal with complexity in all contractually relevant respects which means that incomplete contracting is inevitable

2. opportunism - behaviour by a party to a transaction designed to change the agreed terms of a transaction to be more in its favour [101]

Originally used to understand the organisational and market structures, as Williamson [96, p. ix] states, "Any problem that can be formulated, directly, or indirectly, as a contracting problem can be investigated to advantage in transaction cost terms." Shelanski and Klein [102] note that the aim of TCE is to "explain contracting arrangements observed in practice. Where possible, TCE tries to explain these phenomena on efficiency grounds." TCE has typically been used to consider questions of the most efficient form of organisation for a particular economic relationship, e.g. make or buy decisions, through analysis of historic data (typically using a case study approach) and Reindfleisch and Heide's [103] review of empirical studies of the TCE framework found broad support for the claims of TCE.

Williamson [95] identifies the critical dimensions for describing transactions as "(1) uncertainty, (2) the frequency with which transactions recur, and (3) the degree to which durable, transaction-specific investments are required to realise least cost supply".

1. uncertainty affects transaction costs due to the need to draft complex contracts to deal with many different scenarios

2. the frequency of recurrence of the transaction means that asset specific contracts or agreements can be reused reducing the overall transaction cost

3. asset specificity determines sunk costs which cannot be recovered if the

contract is terminated and lead to a safeguarding problem whereby extensive protections are required in the contract to protect the investment.

This original formulation of the dimensions of transactions and thus drivers for transaction costs has been challenged by many authors and in their review of 54 key articles relating to the application of TCE, Reindfleisch and Heide [103] note that frequency with which transactions recur was not generally held to be an important determinant of transaction costs. In addition, they note that various authors identified multiple dimensions of uncertainty, these are considered in more detail in section 3.5.

3.4 Applying TCE to Energy Performance Contracts

Having justified the selection of Transaction Cost Economics as an underpinning theoretical framework in sections 3.2 and 3.3, it is necessary to clarify how that framework will be applied in this study. While a typical TCE approach seeks to compare the choice of governance structures to determine the most appropriate for a particular context, the aim of this study is to explore procurement decisions made in practice in relation to the scoping of projects. Accordingly, the role of TCE in this study is confined to highlighting characteristics which are expected to influence project viability in order to explore how implementation of those characteristics affects financial results in a practical procurement situation.

Sorrell [22] explicitly applied a TCE framework to analysis of Energy Performance Contracts based on the assumption that "a client's primary motive for entering into an energy [performance] contract is to reduce the total cost of supplying the relevant useful energy streams and final energy services." He noted that an energy performance contract would be expected to increase transaction costs but reduce production costs and thus defined 2 conditions which are necessary for an energy performance contract to be more efficient than an in-house arrangement:

Net savings from the energy performance contract must be greater than the payment to the ESCO.

$$PAY \leq \left(P_{CL}^{IN} - P_{CL}^{EPC}\right) + \left(T_{CL}^{IN} - T_{CL}^{EPC}\right) \tag{3.1}$$

The payment to the ESCO must be greater than the costs incurred by the ESCO.

$$PAY \geq \left(P_{ESCO}^{EPC} + T_{ESCO}^{EPC}\right) \tag{3.2}$$

Implicit in these two conditions is the third, that the total production cost saving must be greater than the total transaction cost increase:

$$P_{CL}^{IN} - \left(P_{ESCO}^{EPC} + P_{CL}^{EPC}\right) \geq \left(T_{CL}^{EPC} + T_{ESCO}^{EPC}\right) - T_{CL}^{IN} \tag{3.3}$$

where:

$$\begin{aligned}
PAY &= \text{Total payment to the ESCO} \\
P_{CL}^{IN} &= \text{Client's production costs for the in-house arrangement} \\
P_{CL}^{EPC} &= \text{Client's production costs for the Energy Performance Contract} \\
T_{CL}^{IN} &= \text{Client's transaction costs for the in-house arrangement} \\
T_{CL}^{EPC} &= \text{Client's transaction costs for the Energy Performance Contract} \\
P_{ESCO}^{EPC} &= \text{ESCO's production costs for the Energy Performance Contract} \\
T_{ESCO}^{EPC} &= \text{ESCO's transaction costs for the Energy Performance Contract}
\end{aligned}$$

Transaction costs include “the staff, consulting and legal costs associated with searching for a supplier, negotiating and writing the contract, monitoring contract performance, enforcing compliance, negotiating changes to the contract when unforeseen circumstances arise and resolving disputes." [22].

For the purposes of this study, installation costs are included in transaction costs since they are a one-off cost while production costs are limited to the cost of energy supply.

Equations 3.1, 3.2 and 3.3 compare two possible procurement options, a business-as-usual approach with no investment and investment energy efficiency measures through an EPC. However, an intermediate option also exists, investment in the energy efficiency measures without the use of an EPC. While UK procurement guidance requires the consideration of alternative procurement options, the explicit consideration of a formal model for direct procurement by the public sector is limited to PFI/PPP projects [104]. This is not a requirement for EPC projects in which the investment in the energy efficiency measures is provided directly by the client as in the cases considered in this study, as detailed in section 4.5.3. Client interviews, reported in section 6 suggested that investment in the energy efficiency measures outside of an EPC would have taken place in a different format, with a different group of potential suppliers, and a direct financial comparison did not form part of the evaluation of procurement options undertaken in practice. The scale of additional data collection requirements necessary to evaluate the potential for procurement outside an EPC framework was beyond the scope of this study as a result. Nonetheless, the financial benefits of the EPC risk transfer are evaluated in section 8.7.3 allowing the maximum economic premium worth paying for the transferred risk to be assessed.

Accordingly, Sorrell proposed 6 new hypotheses for the drivers of transaction costs in Energy Performance Contracting projects:

1. Technical potential for production cost savings for energy services included in the contract - the greater the potential production cost savings the more likely it is that they will off-set increased transaction costs. Sorrell defines the scope of a contract as a measure of the number of different useful energy streams which are included within it and highlights the importance of the breadth of the scope to the technical potential for production cost savings.

2. Aggregate production costs for all energy services within the client organisation (operationalised as size of client) - Sorrell notes that small clients who have limited in-house expertise may find that although large

savings are possible, they are outweighed by transaction costs and postulates that a size threshold will exist below which clients are too small for an Energy Performance Contract to be viable.

3. The specificity of the assets required to provide the energy services included in the contract - asset specificity is held to influence transaction costs as a result of the need for complex contractual arrangements to protect the ESCO's investment in an asset which has low value in an alternative use. Sorrell highlights 3 forms of asset specificity relevant for energy performance contracts:

   Site specificity - the degree to which equipment necessary for the contract has alternative value in another location. However, this assumes that the ESCO has financed the purchase of the asset and retains ownership of it. Under the Mayor of London's RE:FIT framework, for example, the client would typically finance the purchase of any assets and pay the ESCO on completion of the installation [105]. In such a scenario, site specificity would be unlikely to be a particular driver for transaction costs.

   Physical asset specificity - the design and engineering work undertaken by the ESCO. Sorrell notes that in some procurement models this is mitigated by an obligation on the client to pay for detailed design and engineering work if the project does not proceed.

   Human asset specificity - the extent to which specialist knowledge is needed is closely linked to the types of technologies needed. Sorrell argues that ESCOs will necessarily be highly skilled in a range of generic technologies which can be applied to a variety of clients and if specific skills need to be acquired for performance of a contract the ESCO will be exposed to greater risk.

   Although asset specificity is typically considered to be a key pillar of TCE, in the case of Energy Performance contracts it is expected that it will vary primarily between different market sectors. For example, asset specificity will be similar amongst schools but differ between schools and hospitals. As a result this hypothesis is considered useful in testing the likelihood of viability of an Energy Performance Contracting project between sectors but not within a specific market sector.

4. Task complexity as measured by the difficulty of specifying and monitoring contractual terms and conditions - the easier it is to monitor and verify performance the lower the transaction costs both in terms of monitoring costs but also costs which arise as a result of disputed performance.

5. Market competitiveness - in a more competitive market, the potential for opportunism is lower, ESCOs who price bids significantly above marginal costs will not win tenders and so market competitiveness is expected to be linked to lower transaction costs

6. Form of institutional framework - some institutional frameworks may be more or less well suited to undertaking performance contracts. A key aspect of this is the decision-making hierarchy. Complex structures with many layers of intermediate decision makers or a lack of clarity about who is responsible for decision-making will inevitably result in higher transaction costs. Client organisation governance structures will be closely linked to industry sector, particularly for public sector clients where governance arrangements are dictated by the legal powers delegated to the organisation. As a result, this driver would be likely to affect the viability of different sectors but not to explain viability within a particular sector.

3.5 Measuring transaction costs

The TCE framework offers two alternatives for analysis as set out in Chang and Ive [75], namely a direct measurement approach (DMA) or indirect measurement approach (IMA). "For IMA, data is required on measurable *transaction attributes* and on relative frequencies with which governance structures are used, for transactions with different attributes. For DMA, data is required on measurable transaction attributes, the relative sums of all transaction costs for transactions with similar attributes under different governance structures, and the absolute values of the comparatively significant elements of total TCs." The IMA approach is based on the assumption that the most commonly occurring governance structure is the optimal structure while the DMA does not rely on this assumption. However, it relies on the ability to accurately measure transaction costs and there is an additional problem of obtaining enough data for statistically valid assumptions to be made. As Winch [106] notes, "Obtaining good quality data on the 'costs of doing business' is difficult, in that firms do not routinely collect these data, resulting in transaction costs being the 'hidden factory'."

However, while determining the costs of behavioural uncertainty is typically very difficult, in an Energy Performance Contract this is a more straightforward matter, since a reduction in quality can be assumed to result in increased energy consumption which can easily be priced. Equally, additional costs required that might be incurred in addressing opportunism can be defined as the need for investment in additional energy conservation measures to address a potential shortfall in performance. For these reasons, the Energy Performance Contracting Market is considered to be well suited to the use of a DMA approach. Nonetheless, not all aspects of transaction costs can be so easily determined, Reindfleich and Heide [103] define two types of transaction costs as shown in table 3.5.1: direct costs and opportunity costs. Direct elements (costs of crafting safeguards; communication, negotiation and coordination costs; screening and selection costs; measurement costs) are clearly capable of being measured. However, although the sources of opportunity costs are clear (e.g. there may be no incentive for the ESCO to invest in ECMs which would result in savings above the agreed level resulting in a failure to invest in productive assets), quantification of opportunity costs would be a speculative exercise and consequently these costs are excluded from the quantitative

Table 3.5.1: Sources and types of transaction costs

	Asset specificity	**Environmental uncertainty**	**Behavioural uncertainty**
A. Source of transaction costs			
Nature of governance problem	safeguarding	adaptation	performance evaluation
B. Type of transaction costs			
Direct costs	costs of crafting safeguards	communication, negotiation and co-ordination costs	screening and selection costs (ex ante) measurement costs (ex post)
Opportunity costs	failure to invest in productive assets	mal-adaption, failure to adapt	failure to identify appropriate partners (ex ante) productivity losses through effort adjustments (ex post)

analysis in this study. Chapter 6 considers the evidence from the interviews for the existence and likely scale of these costs.

In this study an attempt is made to address the concerns raised by Chang and Ive [75] concerning the difficulty of collecting data for a statistically valid assessment of transaction costs through the use of statistical modelling. If the probability distribution of the elements of transaction costs can be sampled from their input distributions then multiple versions of the model can be calculated to derive a probability distribution for the model output [107].

In order to apply a direct measurement approach equations 3.1 and 3.2 must be summed over the period of the analysis, which may not be the same as the contract duration:

$$\sum_{i=1}^{n} PAY \leq \sum_{i=1}^{n} \left(P_{CL}^{IN} - P_{CL}^{EPC}\right) + \sum_{i=1}^{n} \left(T_{CL}^{IN} - T_{CL}^{EPC}\right) \tag{3.4}$$

$$\sum_{i=1}^{n} PAY \geq \sum_{i=1}^{n} \left(P_{ESCO}^{EPC} + T_{ESCO}^{EPC}\right) \tag{3.5}$$

where n is the number of periods over which the analysis is undertaken.

3.6 Research Hypotheses

The research hypotheses for this study take as their starting point, those set out by Sorrell, as detailed in section 3.4 above. Viability of a project is defined as satisfying the conditions set out in equations 3.4 and 3.5, namely that production cost savings at least off-set transaction cost increases for the client and the ESCO's income at least off-set costs.

As discussed in section 3.4, two of these hypotheses, the impact of asset specificity and that of institutional form, are likely to be closely related to market sector. Consequently, testing these hypotheses would require a multi-sectorial analysis. The resource constraints of the current study preclude such an analysis and the study has been focused on the four hypotheses which should be capable of being explored within a single market sector.

The remaining 4 hypotheses are closely linked to the key procurement decisions of project scale, scope and level of risk transfer, highlighting potential mechanisms for the impact of each and thus form the basis of this study.

- **Hypothesis 1**

  Lower transaction costs will result from a more competitive market.

  As a result increasing market competitiveness should drive down transaction costs and increase the likelihood of project success.

- **Hypothesis 2**

  The easier it is to measure and verify changes in energy consumption the more likely a project is to be viable.

  The fundamental difference between an EPC and a traditional procurement is the existence of the performance guarantee which transfers the risk of achieving the energy savings after installation from the client to the ESCO. However, the extent to which risk is transferred will be determined by the ease of measuring energy savings since the risk is only transferred if performance (or lack of) can be proven.

- **Hypothesis** 3

  An EPC project is more likely to be viable when the range of energy conservation measures included is large

- **Hypothesis** 4

  Increasing the size of a project by increasing the number of facilities included in it increases the likelihood of viability.

These hypotheses are used to guide the exploration of the key research question:

How do project scale, scope and risk transfer influence financial returns for clients and ESCOs?

The market sector chosen for this analysis is the UK schools sector. Chapter 4 sets out this context and details the methods that will be used for this analysis.

Chapter 4

Methods and Data Sources

4.1 Overview

Chapter 2 highlighted a lack of research which would inform the procurement decisions which clients are routinely making in practice, shaping projects which are then put out to tendered and delivered. Chapter 3 identified four research hypotheses drawing on the work of Sorrell [22] which provide some insight into how critical project dimensions of scale, scope and risk transfer might impact on project outcomes. This chapter sets out the methods which are used to explore these hypotheses in an attempt to provide insights which will be of use in structuring future procurements. This chapter also considers the need for a rigorous assessment of uncertainty (as highlighted by the literature review in contained in chapter 2). The context in which the hypotheses will be explored is explained.

4.2 Research methods

The four research hypotheses derived in chapter 3 offer explanations for how choice of project scale, scope and risk transfer might be expected to affect project outcomes.

- **Hypothesis 1**
  A more competitive market will result in lower bid costs and thus a higher likelihood of project success.

- **Hypothesis 2**

  The more accurately measurement and verification procedures measure actual changes in energy consumption the greater the likelihood of project success.

- **Hypothesis 3**

  Technical potential for production cost savings – an EPC project is more likely to be viable when the range of energy conservation measures included is large.

- **Hypothesis 4**

  Aggregate production costs – increasing the size of a project by increasing the number of facilities included in it increases the likelihood of viability.

Two principal approaches to exploring the research question were considered:

- Market data analysis – this approach would involve identifying potential success factors from the literature from which measurable variables can be constructed. Market participants would then be surveyed to determine values for variables which could then be used to conduct a regression analysis to determine the importance of each variable.

- Modelling of individual projects – this approach is based on simulation of a variety of projects to assess the importance of the identified factors for project success.

These two approaches have benefits and shortcomings, in particular, the identification phase of the market data analysis approach allows for a wider range of potential success factors to be explored and potential confounding variables to be identified. However, the key weakness of this approach lies in the difficulty of measuring project success: a completed project is not necessarily a successful one, particularly not for both parties. Obtaining data on whether or not projects have been successful depends on that data being available and there are strong incentives for individuals and organisations to minimise the effects or appearances of unsuccessful projects.

In a modelling approach, simulation results provide a measure of success for each configuration explored. However, the model is constrained by its definition and the selected input data meaning only the predetermining factors can be explored. This can be addressed through a systematic exploration of potential input factors as in the market data analysis approach. However, such an exploration is resource-intensive and beyond the scope of the current study. Consequently, the exploration focused on a sub-set of factors identified in the TCE literature reviewed in chapter 2. Namely, those factors which be varied at an operational level. While there are undoubtedly a range of other factors which potentially affect the success of an EPC project, such as the level of experience of the client, political support and management structures, these are beyond the scope of operational decision making. Instead, this study focuses on three critical dimensions of projects: their scale, scope and the level of risk transfer. As seen in chapter 3, these are closely related to the prediction of the TCE literature. The existence of other potential factors is likely to affect costs associated with a project and the approach taken in this study is to attempt to collect data from a representative range of market participants in order that the range of input data covers these possibilities and to use stochastic sampling to select from the input data.

4.2.1 Modelling Approach

The conditions for viability of a project were defined in equations 3.4 and 3.5:

$$\sum_{i=1}^{n} PAY \leq \sum_{i=1}^{n}(P_{CL}^{IN} - P_{CL}^{EPC}) + \sum_{i=1}^{n}(T_{CL}^{IN} - T_{CL}^{EPC}) \tag{3.4}$$

$$\sum_{i=1}^{n} PAY \geq \sum_{i=1}^{n}(P_{ESCO}^{EPC} + T_{ESCO}^{EPC}) \tag{3.5}$$

These two equations define a bi-partite cash-flow model similar to that proposed by Zhao [108], driven by the fact that a project will only proceed if both parties to it are comfortable with their expected returns. However, although standard accounting techniques have the benefit of being easily understood by industry practitioners, they also have significant shortcomings. Jackson [109] reports on the near-universal use of simple payback as a risk-screening tool for organisations making investment decisions, with a short payback indicating a low-risk investment. Heo et al. [110] make the important observation that one unintended consequence of the energy savings guarantee will be that "ESCOs are less likely to recommend high-impact, high-cost technologies, unless the probability of energy savings can be quantified appropriately and associated risks expressed such that comparison between competing technologies is explicit." Together with Zhao [108], they point to the inadequacy of standard, deterministic energy modelling to achieve this.

Review of the literature presented in chapter 2 identified the following elements of good practice to be incorporated in the analysis in this regard:

- probabilistic simulation of energy savings using building energy simulation, combined with parameter screening to reduce computational load
- probabilistic simulation of energy price volatility
- variability of the performance of energy conservation measures over time should be considered
- variation in weather over time should also be considered

A statistical modelling approach relies on the quantification of uncertainty encompassed by the probability distributions of the input factors. As a result it is necessary to first define what is meant by uncertainty. Knight [111] draws a distinction between uncertainty which is measurable, and theoretically at least, knowable, and risk, which is not. Stirling [112] describes risk as " possible effects of actions, which are assessed as unwelcome by the vast majority of human beings." In the context of this study, risks can be thought of as failures

– for example, energy conservation measures which are faulty, failures of workmanship, time over-runs caused by delays in reaching agreement on contract terms. Although the occurrence and outcome of a risk event are uncertain and in many industries, for example - the nuclear industry - considerable time and effort is expended in eliciting the likelihood of occurrence and the probable impact [112, p. 15], these risks are capable of being avoided or mitigated and addressed through contractual remedies. Nonetheless project outcomes are still not perfectly known because uncertainty still remains.

Uncertainty falls into two principal categories [113]: aleatory uncertainty (which results from inherent randomness in the parameter) and epistemic uncertainty (which results from a lack of knowledge). These categories of uncertainty are sometimes referred to respectively, as first and second order uncertainties [114]. Epistemic uncertainty is particularly important in a time-constrained commercial context where it is not financially viable to undertake the level of investigation necessary to increase knowledge, e.g. determining the thickness of an interstitial insulation layer, even if it is technically possible. The existence of building occupants who interact with the building and its systems means that aleatory uncertainties are also significant. A modelling study which combines these elements should result in the rigorous approach to uncertainty quantification advocated by Wang et al. [63]. This is particularly important in the context of the "open systems" [115] of the natural world where it is necessary to reject the idea of only one optimal model being the most reliable for a particular situation. In an open system, many different model structures and parameter sets may give simulations that cannot be falsified from the available observational data.

The need to understand the impact of uncertainty in model inputs on the output response drove the selection of probabilistic modelling as the basis of this study. Stochastic sampling from the probability distributions of individual model inputs allows uncertainty to be propagated through a model in order to create a distribution of model outputs from which inferences can be made using the the NPV-at-risk approach proposed by Ye and Tiong [116].

It would be overstating the case to suggest that probabilistic modelling can overcome all of the shortcomings of a deterministic approach and in particular, it is still subject to Lemons et al.'s criticism that "not recognising the 'value laden' nature of the framing assumptions used in modelling", results in studies appearing "more factual and value-neutral than warranted" [117]. This applies particularly in the initial, often unrecognised phase of deciding which parameters are likely to be influential (and thus merit the time-consuming process of collecting data on likely distributions) and which can be assumed to be fixed.

4.3 Overview of model inputs

Developing input data for the DSCF model requires the collection of very different types of data, each with different methodological requirements. The different types of data and the mix of methods required to collect them are summarised here to provide context for subsequent sections which discuss the individual data sources in more detail. Figure 4.3.1 below illustrates how the model inputs are generated and fed through into the Discounted Cash Flow (DSCF) model. Uncertain inputs are modelled as probability distributions from which input values are sampled to generate an output probability distribution.

Many of the data collection choices were driven by the commercially sensitive nature of the information being sought. In particular, since divulging details of real projects could have serious consequences for respondents this was considered unethical. Using hypothetical projects allowed respondents greater freedom to respond but also allowed more straight-forward comparison between projects. However, using hypothetical projects has the consequence of placing a greater burden on the respondent, since all data must be created, rather than simply reported. In addition to creating an onerous response requirement, this also raises significant issues of validity. Consequently, it was decided to focus the interview-based data collection on those aspects for which no other data source existed, namely, transaction costs, and to use alternative data sources for other elements of data. However, although this approach reduced the interview data collection to a manageable level, it introduces additional risks. Most significant of these is the potential for overlap and gaps between the different costs. The potential for double counting is greater than the likelihood of elements being missed altogether. Attempts were made to reduce this risk through careful sequencing of the data collection process in order that the hypothetical projects were fully defined before being priced and the interview responses sought. Consistent definitions of the categories of costs sought were provided to respondents but it is still possible that some elements of cost included in the installation costs may have been included in the transaction cost estimates provided. This would have had the effect of inflating transaction costs. However the effect would be consistent across all project responses which would mean that comparisons between projects of different scales and scopes would still be valid.

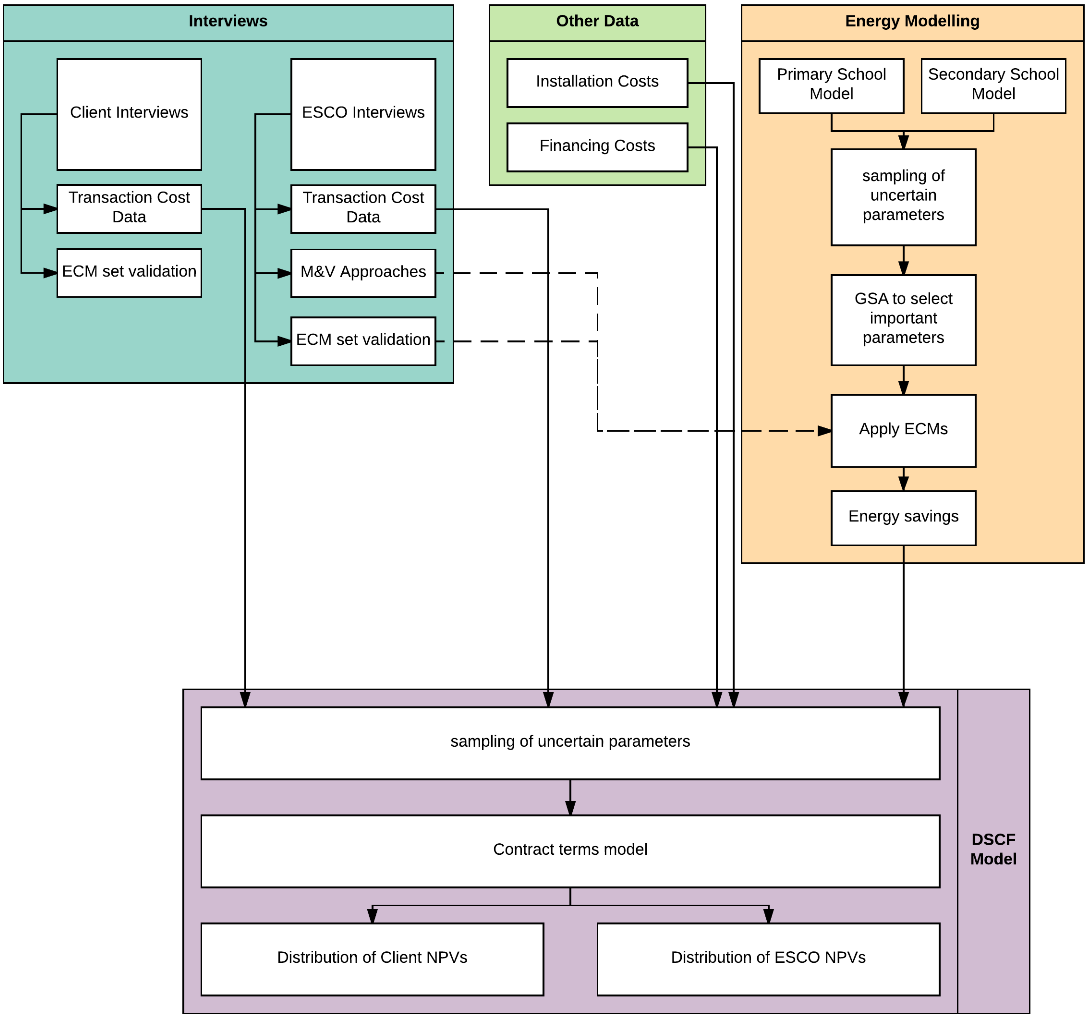

Figure 4.3.1: Data structure

Table 4.3.1: Overview of model inputs

Data	Collection	Reported
Client transaction costs Internal costs of developing project, running competition and selection process, contract negotiations, managing contract External support costs including legal fees, survey costs, M&V costs	semi-structured interviews	Section 6.2.2
ESCO transaction costs Costs incurred at risk to win contract including design and survey costs Financial, legal and administrative costs required to reach contract signature On-going project management costs Gross Margin	semi-structured interviews	Section 6.2.1
Installation costs	Provided by Quantity Surveyor	Appendix F
Financing costs	literature review and interview results	Table 4.5.1
Energy savings	2 building archetypes modelled in energy plus	Chapter 5

Only direct costs associated with the EPC are included, including the percentage of overheads attributable to the project. Since no specific tax incentive programme exist in relation to the ECMs considered these are not included.

4.4 Development of the modelling framework

The focus of the remainder of this chapter is on the development of a stochastic bi-partite DSCF model and transaction cost inputs. The development of energy saving inputs is addressed separately in the following chapter. Refsgaard and Henrisksen [1] propose a framework to deal with concerns about the validity of a modelling approach by making explicit the steps in model development and considering the framing decisions and their implications as part of the modelling process. Their guidelines are illustrated in figure 4.4.1 below. These guidelines have been used as a framework for developing the DSCF model based on equations 3.4 and 3.5.

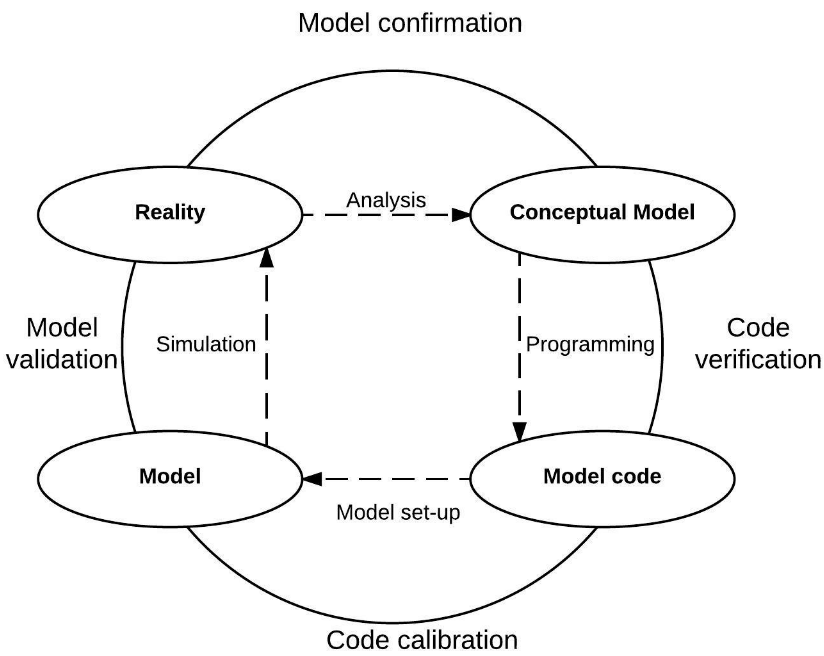

Figure 4.4.1: Refsgaard and Henriksen's modelling framework [1]

The real situation which is being modelled is described in section 4.5. The process of analysis of that reality, as represented by the form of contract used, to develop a conceptual model of the situation, and subsequent confirmation of the model is described in sections 4.5.1 and 4.5.3. The model code which results from the translation of the conceptual model into a computer model is available at the location detailed in Appendix A. Code verification was undertaken through a process of sequential testing of code segments with test data constructed to produce expected outputs, together with testing with extreme values. The model set-up is detailed in section 5.2. Finally, the model is run to produce the required simulations of reality. Since the underlying case studies which are being simulated are hypothetical, the final step of model validation cannot be explicitly undertaken since there is no calibration data with which the model outputs can be compared. This has necessitated a focus on the validity of the underlying model inputs which has been described for transaction costs in section 5.2, and for production costs in section 5.3.5.

4.5 Context

The UK EPC market has recently been well summarised by Nolden and Sorrell [19] who identified two defining characteristics - firstly, that the market is dominated by the public sector, with business risk being a key barrier to development of the industrial sector, and split-incentives acting as a significant brake on the commercial office sector. Secondly, the rate of growth of the public sector market has been partly due to the development of public procurement frameworks (PPFs). PPFs allow a group of contractors to be procured through a process which is compliant with EU regulations on competitive procurement, ahead of any projects being developed. Individual clients can then run a competitive process within the group of pre-selected contractors and use standard contract terms which results in reduced transaction costs. Nolden and Sorrell identified 5 active PPFs in 2014:

- RE:FIT originally established in London to serve local authorities and other public sector bodies and subsequently used as a template for the Local Partnerships England-wide PPF
- Carbon and Energy Fund (CEF), focusing on the health sector
- Essentia, health care focussed
- Ecovate, healthcare focused
- P-EPC established by Peterborough City Council.

The most active of these frameworks are RE:FIT and CEF. More recently, RE:FIT Cymru has been launched to target the Welsh market and the Scottish government has launched the Non-Domestic Energy Efficiency Programme (NDEE). The RE:FIT model can be characterised as a guaranteed savings model with no sharing of excess savings, whereas the CEF is a shared savings model [43].

4.5.1 Conceptual model

The UK schools sector was selected as the subject of interest for this study since it is a sector which has high reported potential for abatement [118] and represents an important element of the UK non-domestic building stock's energy consumption: the UK Government Department for Business, Energy and Industrial Strategy (BEIS)'s 2014-2015 Building Energy Efficiency Survey reports that primary and secondary schools represent approximately 7% of the UK's non-domestic building stock by floor area and are responsible for 3% of non-domestic electricity use and 5.3% of non-domestic fossil thermal energy use.
Further justification for the selection of primary and secondary schools as the subject of interest for this study comes from their relatively homogeneous nature: the BEIS study reports that 'Based on the floor area weighted records, premises in the education sector had broadly common characteristics, with the exception of nurseries', namely that primary and secondary schools are typically owner-occupied (84% for primary schools and 79% for secondary schools) and are the sole occupier of their premises (100% for both primary and secondary schools). 62% of primary schools and 45% of secondary schools were constructed between 1940 and 1990. These characteristics are important because they mean that factors which might impact on a client's desire to undertake an energy efficiency investment such as site complexity or split-incentives due to building tenure are not prevalent in this sector.

The RE:FIT framework [105] is the only UK PPF specifically tailored to the local authority sector in England. Accordingly, the RE:FIT contract was used as the basis for structuring cash-flows within the model [119].

4.5.2 Model code

The model was developed in Matlab [120] and the code is included in appendix A. The following section explains the logic of the treatment of flows within the model. The model time-line follows the indicative time-line set out in the RE:FIT guidance issued to local authorities [121]. This comprises five phases, as shown in figure 4.5.1, although the effects of the installed measures may well continue after the end of the guarantee period:

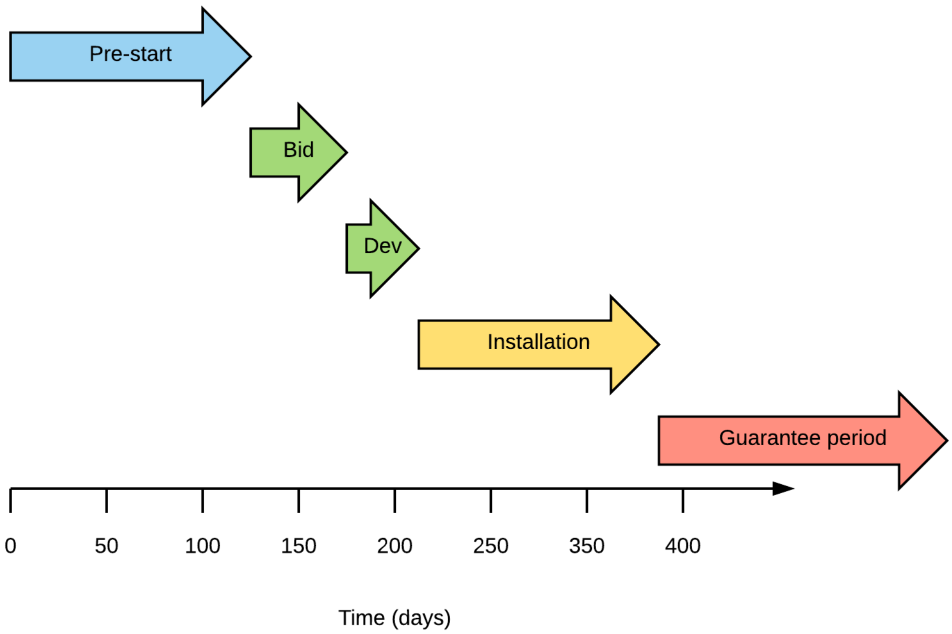

Figure 4.5.1: Typical RE:FIT project time-line

1. Pre-start - during this phase only the client is active, collating data, securing approvals and producing tender documentation. This phase lasts 130 days

2. Bid phase - during this phase the authority runs a mini-competition among the framework providers who have expressed an interest in participating in the project. This phase lasts 50 days. During the course of the second RE:FIT framework an alternative procurement model was introduced - the "partner bid" model. In this model, the preferred bidder

is selected earlier in the process and the balance of time is shifted from the bid to the development phase as a result.

3. Development phase - this begins with the selection of a preferred bidder who will develop their proposals in more detail and ends when all the necessary approvals have been secured and the call-off contract has been signed. This phase lasts 35 days; however, a previous study indicated that this was the phase most likely to be subject to delay [2]. Costs incurred by the ESCO in the bid and development phases are paid by the client as a lump sum at contract signature.

4. Installation phase - following contract signature, the ESCO proceeds with the installation of the agreed energy conservation measures. The duration of this phase is determined by the nature of the ECMs which are due to be installed. It is assumed that this phase lasts 130 days.

5. Guarantee period - energy savings are guaranteed for a period set out in the contract. This is defined endogenously as the simple payback period of the expected savings.

Energy conservation measures remain in place following the end of the guarantee period and the client will continue to benefit from the energy savings during this period. The maximum length of the model is set as 25 years post -installation and the post-guarantee period is defined endogenously.

Previous research indicated that neither clients nor ESCOs would have resources exclusively allocated to a single EPC project [2] and that in the event of a delay to a project, staff time would be spent on alternative activities. Consequently, neither ESCO nor client would expect to incur additional costs in the event of a project delay and the project timescales have been treated as fixed in the model as a result.

Equations 3.4 and 3.5 are applied as follows:

- $(P_{CL}^{IN} - P_{CL}^{EPC})$

  Energy cost savings as a result of the energy conservation measures installed. These are treated as a positive cash-flow in the model, accruing to the bill payer. In the guaranteed savings model described above, this is the client. Chapter 5 details the calculation of these costs.

- T_{CL}^{IN}
  Client's transaction costs for the in-house arrangement, since this is a continuation of the existing utility procurement arrangements with no energy conservation measures installed, the transaction costs are zero.

- $(T_{CL}^{EPC} + T_{ESCO}^{EPC})$
  Client's transaction costs for the Energy Performance Contract. This is a combination of the client's internal transaction costs and the costs charged by the ESCO. ESCO transaction costs are paid as a lump sum at contract signature. Installation costs are incurred monthly by the ESCO during the installation period and repaid by the client in a lump sum at the end of the installation period. A margin is added to the installation costs - this represents the ESCO's profit on the project and is paid by the client at the end of the installation period.

- P_{ESCO}^{EPC}
  ESCO's production costs for the Energy Performance Contract. During the guarantee period, differences between the expected savings and the actual savings are treated as a flow from the ESCO to the client. ESCO shortfall payments are calculated as the difference between the measured and expected energy savings for each option multiplied by the appropriate contract energy price. The contract energy prices are the current energy prices at the model base date uplifted by an agreed index.

This definition of transaction and production costs reflects that proposed by Whittington [122] in her transaction cost analysis of highways infrastructure projects.

In line with HM Treasury guidance [104], all cash-flows are presented in real terms.

4.5.3 Model confirmation

Refsgaard and Henriksen [1] describe the purpose of model confirmation as being the "determination of adequacy of the conceptual model to provide an acceptable level of agreement for the domain of intended application". The DSCF model represents the monetary flows to and from the client and ESCO in an energy performance contract, and follows the form of the Mayor of London's RE:FIT framework agreement [119]. The framework agreement was analysed using the United States Office for Energy Efficiency and Renewable Energy's (EERE) energy performance contract risk, reward and performance matrix [123], as set out in table 4.5.1. This matrix is a well tested list of key risks and contractual provisions which can be applied to compare energy performance contracts and allow the contracting parties to understand their risk allocation under the contract. In table 4.5.1 the headings contain the list of key issues set out by the EERE. The first column sets out the RE:FIT contract position on the issue while the second explains the modelling treatment.

In January 2015, the UK Department of Energy and Climate Change (DECC) issued a model energy performance contract and guidance note to be used in the RE:FIT national programme [124]. This contract was developed from the RE:FIT contract to allow usage by procuring organisations outside London who would not have access to procurement support provided under EU ELENA funds. As a result a comprehensive guidance note is included with this version of the contract. The DECC contract is identical to the RE:FIT contract save for changes to reflect the procurement arrangements and some adjustments to thresholds, therefore, where a contractual provision is unclear in the original RE:FIT document, clarification was sought from the DECC guidance note. It is important to note that the aim of this study is to explore the range of probable outcomes arising from aleatory and epistemic uncertainty inherent in the systems under consideration; the study does not seek to explore the results of failures and errors in the system, for example, the risk of underestimated installation costs or the impacts arising from failures of individual energy conservation measures which have been installed. Inclusion of such errors and failures would increase the weighting of negative outcomes.

Table 4.5.1: Translation of RE:FIT contract into DSCF model

RE:FIT contract position	Derivation and treatment in model
1. Financial	
a. Interest rates post contract signature	
The contract does not contain terms for installation works as these would be procured by the client using their standard terms [124, p. 8]. Consequently finance for works is typically provided by the client	It is assumed that Salix funding is used [125] which provides interest-free funding for schools energy efficiency projects with a payback period of up to 8 years. Where the payback period is greater than 8 years, additional finance is assumed to be provided by the client at the Public Works Loan Board rate applicable for the length of the loan required [126]
b. Construction costs post contract signature	
See (a) above	The client's preferred terms are expected to be standard forms of contract e.g. the Joint Contracts Tribunal's (JCT) works contract which will set out the conditions under which the contractor can claim for additional costs from the client. Since the focus of this research is on the performance guarantee, variations in cost during the construction period are excluded from the DSCF model
c. M&V confidence (IPMVP option selected?)	

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RE:FIT contract position	**Derivation and treatment in model**
The RE:FIT framework agreement requires the ESCO to provide "measurement and verification services" but does not relate these to any standards [119, p. 131], while the DECC guidance note references IPMVP but does not specify an option [124, p. 18]	The International Performance Measurement and Verification protocol [79] sets out four alternatives for measuring and verifying energy savings, the M&V options. Each option has a different measurement boundary as described in Fennell et al. [2]. Option D, calibrated computer simulation, is excluded from this study as discussed in section 7.3. For each energy conservation measure, expected savings are calculated using a deterministic approach. It is this figure which is used to calculated the simple payback period and, in turn, sets the length of the guarantee period. The measurement boundary for each energy conservation measure and each M&V option is detailed in section 5.2.3 below.
	The model is designed to evaluate one of the case study projects at a time, with the results for each combination of prices and M&V scenario being computed.
c. M&V confidence (Responsibility for M&V?)	
See above	ESCO costs for the M&V phase were elicited during interviews
d. Energy Related Cost Savings	

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RE:FIT contract position	Derivation and treatment in model
Calculation of energy savings and the guarantee mechanism are contained in cl. 9 of sch. 2A to the RE:FIT contract [127, p. 78]	cl. 8 of sch. 2A of the RE:FIT Framework Agreement [127, p. 78] sets out a warning notice regime in relation to the performance of individual retrofit measures to address failure of individual measures. The failure of an ECM is excluded from this study.
e. responsibility for changes in energy prices	
to be agreed by contracting parties [124, p. 16]	The risk of varying energy prices over time is considered a significant one by most market participants as discussed in section 2.3.2. This variability is modelled using three alternative energy price scenarios as discussed in section 5.5. Interview responses indicated that ESCOs would typically agree an indexation to be applied to current energy prices at contract signature to avoid the risk of potentially large increases in future energy prices. The indexation factor was based on UK general inflation index (RPI) but treated as a stochastic variable to allow the impact of uncertainty in its value to be considered. In the event of an energy saving shortfall, the ESCO penalty is based on the shortfall quantity multiplied by the indexed price and not the prevailing energy price.
f. indexation mechanisms	

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RE:FIT contract position	Derivation and treatment in model
In contrast with the previous version of the RE:FIT framework agreement, no explicit guidance is provided on indexation mechanisms in the current framework agreement.	The only ongoing costs in the model are energy costs, indexation of which is addressed above and in section 5.5. Previous work [2] indicated that as on-going maintenance was often the subject of a separate out-sourcing agreement, on-going maintenance and life cycle costs are typically excluded from energy performance contracts and this approach was followed in this study.
	Based on interview responses,the costs of M&V services are capitalised into the installation costs, and consequently indexation is only applied to align costs within the model to the same base date and to update the initial model energy prices for the purposes of calculating the price shortfall payable by the ESCO. The current value of the retail price index is used for this purpose [128].
g. Delays	
The RE:FIT framework agreement contains provision for liquidated damages in cl. 41.2 of sch. 5 [127, p. 52]. However, their inclusion is at the discretion of the parties.	It is assumed that both parties bear their own costs in the event of a delay. However, the size of the projects means that staff will not be working exclusively on these projects and in the event of a delay, resources would be diverted to other projects. As a result, project dates are not treated as variable in the DSCF model although in practice delays do often occur.
h. Major changes in facility	

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RE:FIT contract position	**Derivation and treatment in model**
The definition of the baseline level of utilities consumption in sch 3. of sch. 5 [127, p. 73] allows for adjustment to take account of changes in the scope or nature of the premises.	Changes are excluded from the DSCF model.
2. Operational	
a. Operating hours - Are operating hours measured or stipulated?	
Premises operating hours are intended to be defined by the client at the start of the competitive process.	Operating hours of individual building systems are not explicitly discussed in either form of contract and, in practice, the approach to determining these is likely to be decided by the choice of M&V option. This is typically a trade-off between cost and accuracy. Operational hours are treated as variable inputs in the model and the input distributions for each are defined in appendix B
a. Operating hours - What effect do changes in operating hours have?	

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RE:FIT contract position	**Derivation and treatment in model**
Changes to operating hours are not dealt with expressly in the contract.	In practice, the official working hours for the premises and the actual occupied hours may differ significantly. In addition, operating hours for building systems may vary considerably from designated working hours. As a result, differences between expected and actual operating hours are addressed through the M&V options with responsibility for costs arising from a difference between the two, varying depending on how the energy savings are measured.
a. Operating hours - Changes in occupancy-levels?	
As above, changes in occupancy levels would be a variation to the Project Brief	Some diversity in occupancy levels is included within the probabilistic inputs to the energy model as detailed in appendix B, significant changes are excluded from the DSCF model
b. Load - Measured or stipulated?	
Not detailed in contract	Addressed through M&V option
b. Load - Who is responsible for changes?	
If detailed in Project Brief changes would be a client variation	Changes in load are excluded from the DSCF model
c. Weather (responsibility for weather-related changes in consumption)	
Not detailed in contract	As detailed in the IPMVP [79], changes in weather are typically addressed through heating degree day adjustments. It is assumed that this is the case in the DSCF model. Section 5.3.5 discusses the potential consequences of this.

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RE:FIT contract position	**Derivation and treatment in model**
d. User participation (behaviour change programmes?)	
Not detailed in contract	Interviews with clients and ESCOs suggested that behaviour change programmes were considered in addition to the performance guarantee and were not included within the guaranteed savings. Consequently, behaviour change programmes were excluded from the measures modelled
3. Performance	
a. Equipment performance	
Determined by project-specific works agreements	Equipment failure is excluded from the DSCF model
b. Operations - Responsibility for day-to-day operation of equipment	
Project specific	Service provision is excluded from the DSCF model. Costs associated with the ongoing operation of equipment would be a client responsibility but are not included within the DSCF model. It is possible that this could result in an under-reporting of savings over the life of the project; however, these costs are difficult to quantify and often depend on existing contractual arrangements meaning they may well remain unrealised by the client.
c. Preventive Maintenance	
Project specific	see above

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RE:FIT contract position	**Derivation and treatment in model**
d. Equipment Repair and Replacement - Responsibility for repair and replacement of failed equipment (including at end of life)	
Project specific	see above
Concluded	

The conceptual model is illustrated in figure 4.5.2 and can be summarised as follows:

- Both ESCO and Client incur costs prior to contract signature. At contract signature ESCO transaction costs are reimbursed by the Client

- Installation of ECMs is governed by a separate JCT works contract, the ESCO bears installation costs during the installation period. On completion of installation the Client makes a payment to the ESCO which covers the installation costs plus a profit margin for the ESCO. These payments are fixed in the contract

- Following installation of the ECMs the client receives energy savings. The amount of cost savings are dependent on the energy savings and the prevailing energy price

- During the guarantee period, actual energy savings (kWh) are compared with guaranteed energy savings (kWh). In the event of a shortfall, the ESCO makes a penalty payment to the Client. The penalty payment is based on the energy shortfall and the indexed energy price.

4.6 Determining transaction costs

4.6.1 Types of transaction cost

A transaction is defined as the “transfer of a good or service across a technologically separable interface" [92, p. 552]. While there is a wide body of

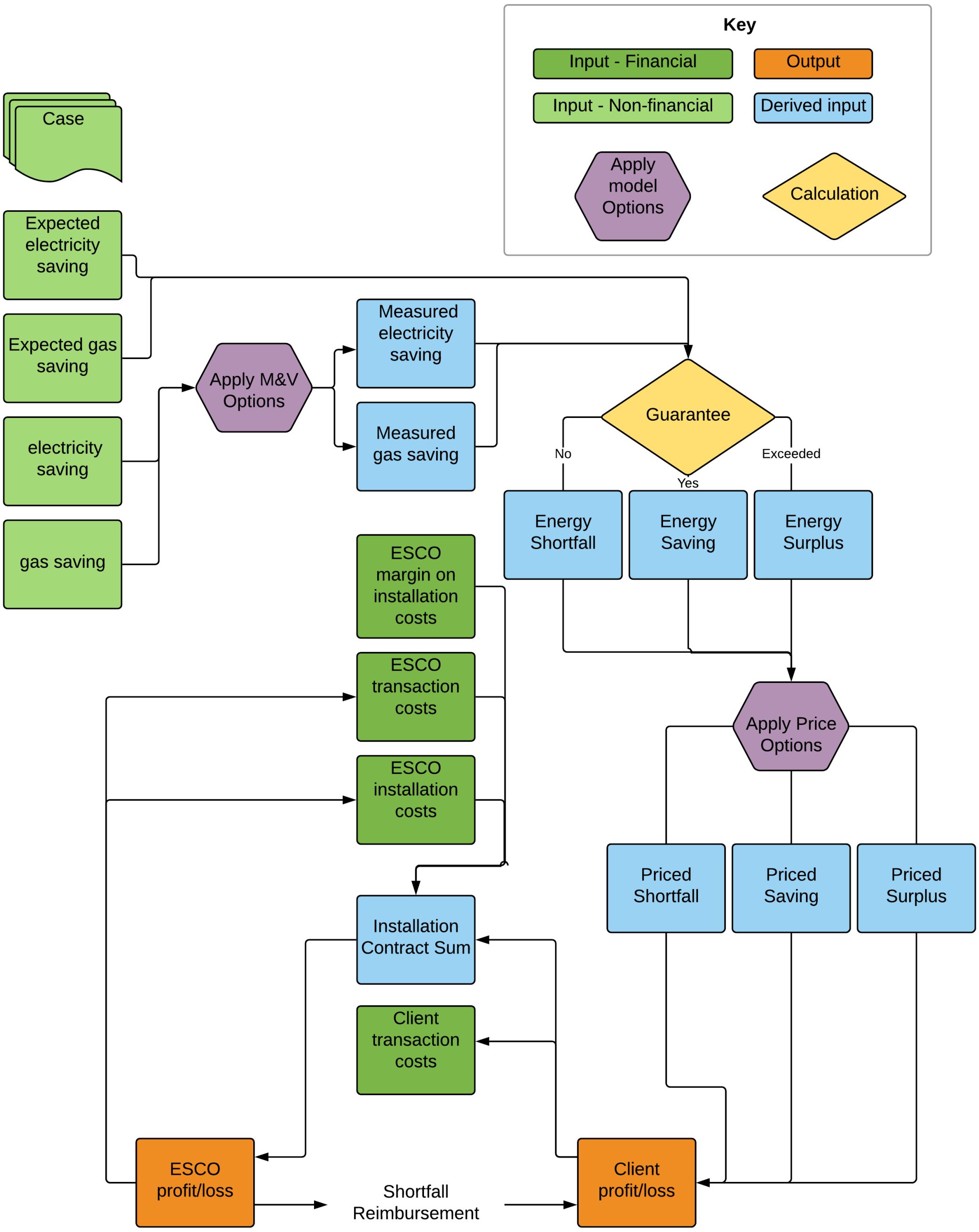


Figure 4.5.2: Model logic diagram based on guaranteed savings contract

literature recognising the importance of transaction costs to strategic decision making in organisations e.g. [23]. Dahlman [91] sets out the principal elements of transaction costs as:

- Pre-contracting stage – search and information costs – bid costs

- Contracting stage — bargaining and decision costs - project development costs

- Post-contracting costs – policing and enforcement costs - measurement and verification costs

Chang and Ive note that “The success of DMA is conditional on whether the precise estimate of these costs can be obtained empirically.” [75, p. 8]. Chang and Ive follow Dahlman’s [91] assertion that transaction costs are rooted in lack of information and characterise this as a two round information problem: The first round occurs due to search and information costs to reduce the information deficit and results in real resource-incurring transaction costs (TC_I), the second round occurs due to the intersection between bounded rationality and opportunism as parties attempt to exploit information asymmetries to their advantage (TC_{II}). These two information problems result in two distinct measurement challenges:

- **Resource-incurring transaction costs (TC_I)** Although resource-incurring transaction costs are well-understood by ESCOs (who are required to report them explicitly in RE:FIT tender submissions), they are expected to be considered to be commercially sensitive information. For Clients, these costs might be less commercially sensitive but without the commercial imperative to identify costs on individual projects, it is likely that disaggregation of staff costs into those incurred on individual projects will be difficult. In order to overcome these challenges, an approach was developed using hypothetical projects which would allow respondents to provide transaction cost data without revealing confidential information. This approach was tested in an initial feasibility study with 2 clients and 2 ESCOs and found to be successful in addressing respondent concerns. [2].

- **Rent-transferring transaction cost (TC_{II})** Chang and Ive highlight the importance of quantifying transaction costs that arise due to behavioural uncertainty or opportunism - “the negative difference between the promise (on the basis of which the transaction are agreed) and the delivery or out-turn" [75, p. 11]. They refer to this as rent-transferring transaction costs. In Whittington’s [122] ex post analysis of transaction costs for highways projects, she was able to include data on out-turn costs as well as predicted costs and thus quantify the costs of change orders during the works. While such data is not available in the context of hypothetical projects, it is possible to infer the out-turn prices by considering the mechanisms through which such costs could arise and attempting to quantify them. Whittington suggests that transaction costs arising from unforseeable events can occur at each stage of the contracting process: Ex-ante, the ESCO has undertaken detailed surveys and development work for which it will be paid on contract signature. This work represents sunk costs for for the ESCO, thus presenting a hold-up opportunity for the client who might exploit this to try to extract additional value from the ESCO. Some contractual protection is provided in the RE:FIT framework agreement [129, sch. 2 cl. 5.5] which requires the client to pay the “the reasonable and proper costs of preparation of [the] Investment Grade Proposal as evidenced by the [ESCO]”. Since this is a contractual provision of which bidders are aware prior to bid submission, any risk pricing associated with this is assumed to be included in the bid costs.

Ex-post, during installation, client change orders which are not priced in competition may be used by the ESCO to extract additional value. However, the impact of this will be closely linked to the length of the installation period, since the longer and more complex the installation the greater the risk that specification changes will be required. For buildings which are simple in engineering terms, such as schools, this is not the case and the number of change orders is likely to be very low. A review of data from 142 US projects by Shonder and Slattery [130, p. 3] supports this view with changes in the guaranteed energy savings post contract award identified in only in 10% of projects. Further protection is provided by the requirement for any changes to be priced on an open book basis [129, sch. 2 cl. 7.16]. Consequently, it is assumed that no additional costs arise post-installation as a result of change orders.

Ex-post, following installation, the key risk for the client is that savings may not be as high as expected. Although the savings guarantee is intended to ensure "[t]he Energy Service Company (ESCO) guarantees the savings as set out in the payback calculation from the completion date of the installation of the energy conservation measures" [121, p. 14]; this is a simplified version of the actual situation. As implied in the guidance issued alongside the model contract issued by the Department of Energy and Climate Change (which was based on the RE:FIT programme) [124, p. 2] "If you don't understand the M&V then you won't understand the energy savings and in effect won't understand what you are buying" [124, p. 18]. In practice, because the guarantee can only be applied if a shortfall in savings is demonstrated, the guarantee is defined by the measurement and verification approach selected. This means that the scope of the guarantee is ultimately defined by the M&V strategy and may not be as broad as the client anticipates. In addition, although the RE:FIT "Starter Pack" issued to prospective clients advises that they "will have the option to either ask the ESCO to pay the shortfall or to implement further ECMs, at their cost, to make up the shortfall" [121, p. 14], the mechanism which allows the client to require the ESCO to replace an ECM only applies to specified "Measured Assets" or "Warranted Assets" [129, sch. 2 cl. 8.2–8.3] and would again require the specific shortfall to be measured in order to be implemented. In the absence of this, it will be the ESCO's choice whether to make up the shortfall or implement more ECMs, and since the client would typically expect to enjoy savings from the ECM beyond the end of the contract period this may have a material impact. As a result, by assuming that a savings shortfall which can be substantiated through the M&V process is paid by the ESCO, the worst case scenario for the client can be quantified, and a full approximation of transaction costs arising from the procurement route can be made.

4.6.2 Selection of ESCO participants

The Greater London Assembly's RE:FIT programme appointed 16 businesses as framework suppliers in Spring 2016 [21]. These ESCOs who are active in the only energy performance contracting framework targeting schools were selected as the total potential sample for this study. Analysis of company accounts indicated that the organisations covered a broad range of sizes, ranging from fewer than 50 to more than 10,000 employees, with turnovers ranging from less than £5,000,000 to more than £5,000,000,000. In their 2012 survey of the US ESCO industry, Larsen et al. [52, p. 806] grouped ESCOs into 4 categories according to business ownership "(1) companies that are owned by building equipment or controls manufacturers, (2) companies that are subsidiaries of electric or gas utilities, (3) companies that are owned by other types of energy companies such as gas producers and pipelines, and (4) companies that provide engineering services and are "independent" in the sense that they are not owned by utilities, energy companies, or equipment/controls manufacturers".

Table 4.6.1: ESCO business type and market share

Company type	**No. in Larsen study**	**No. on RE:FIT framework**
Controls	4	1
Energy supply	5	3
Other energy supply	4	0
Engineering services	25	12

Analysis of the definition of business activities on the Companies House register suggested that the engineering services companies fell into 2 distinct categories: organisations with a track record in delivering construction, engineering or facilities management services and smaller organisations, often more recently formed, which are focused more closely on the provision of energy services. Since transaction costs are likely to be partly determined by industry sector, this suggested that transaction costs might vary significantly between the organisations on the framework. The diverse nature of the organisations involved in this market may indicate a diversity of cost structure resulting in different levels of transaction cost for different types of organisation. As a result it was considered necessary to recruit ESCO participants from each category or organisation to ensure this diversity was captured. Figure 4.6.1 illustrates the level of coverage that was achieved.

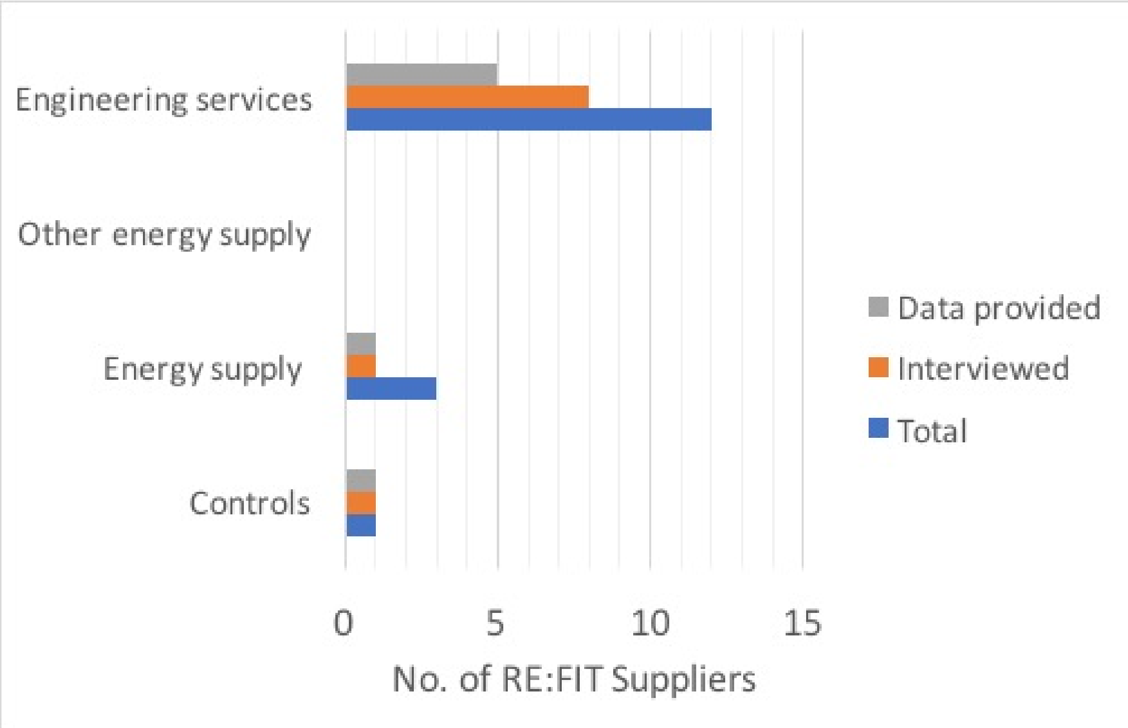


Figure 4.6.1: ESCO participants by sector

4.6.3 Selection of Client participants

Potential client participants were identified through discussions with framework managers. This resulted in a list of names of individuals who had had experience of procuring energy performance contracts in schools through the RE:FIT programme. No definitive details are available in the public domain of local authorities who have undertaken schools energy performance contract projects so it is difficult to be sure of the total potential sample size. Contact details were obtained in this way for a total of 9 client organisations who had undertaken schools projects through the RE:FIT programme, 2 of these contacts were interviewed for an earlier feasibility study [2]. However, one contact had left the organisation and the other's experience of schools projects was not applicable to the scale of the projects under consideration in the current study, and consequently they were excluded. The differences in scale and scope between the case studies used for the feasibility study, and those used for the current study meant that it was not possible to incorporate data from the feasibility study within this study. It was not possible to make contact with 3 of the 9 contacts provided. Interviews were undertaken with the remaining 4 clients.

4.6.3.1 Data collection approach

The purpose of engaging with market participants was to obtain 2 different types of data:

- Quantitative – market participant views of likely transaction costs for the 4 sample projects
- Qualitative – contextual understanding of how the RE:FIT framework is operating in practice and participants experiential learning

Three different approaches were considered in order to obtain this information as shown in table 4.6.2.

Self-administered surveys were rejected as they would only offer limited scope to develop the contextual understanding of the framework in practice. The complexity of this type of data does not lend itself well to a situation where there is no ability to probe answers and the risks of misinterpretation of data were considered to be high [131]. Further, response rates to survey instruments are typically low and given the relatively small size of the potential sample this would compromise the results. Most importantly, the quantitative data sought is commercially sensitive and it was anticipated that respondents would be unwilling to share it unless a degree of trust had been established. Problems of language as identified by Schoenberger [131] are also important as a clear

Table 4.6.2: Characteristics of data collection methodologies considered

Method	**Self-administered survey**	**Standardised interview**	**Non-standardised (open-ended) interview**
Research Design	Extensive and quantitative	Usually extensive and quantitative	Usually intensive and qualitative
Theoretical approach	Commonly used in positivist approaches	Commonly used in positivist approaches	Commonly used in realist and phenomenological approaches
Sample	Representative or whole population	Representative or whole population	Selected to cover a range of phenomena or issues of interest
Interview style	n/a	Minimisation of interviewer related error	Interactive following issues raised in the interview
Questions	Factual and pre-coded questions	Factual and pre-coded questions common	Nearly all questions open-ended

understanding of what costs are included in each item is fundamental to the validity of the information collected.

Many of these issues would also be limitations to a standardised interview and consequently it was decided that non-standardised/open-ended interviews would be the most appropriate technique since it was believed that the open dialogue and intellectual engagement of the participants would increase the accuracy and validity of responses [131].

Huber and Power [132] identify 4 primary reasons that interviewees might give inaccurate or biased information in their review of the literature surrounding data collection from strategic-level managers:

1. They are motivated to do so
2. Their perceptual and cognitive limitations result in inadvertent errors
3. They lack crucial information about the event of interest

4. They have been questioned with an inappropriate data elicitation procedure.

This issues were addressed as follows:

- The study itself may provide motivation for ESCO interviewees to provide inaccurate information. The purpose and format of the research had been clearly explained to all participants, this had the consequence of making it clear to participants that the researcher was in possession of similarly sensitive data from potential competitors. It is possible that some participants might have artificially adjusted their responses to questions in order to elicit a response from the researcher which might result in some commercial information being shared. To reduce this risk it was decided that no interview data would be analysed until all interviews had been completed, and that the final set of aggregated responses would be triangulated by testing with framework managers.

- Interviewees might make errors in the responses they give due to inadvertently including or excluding other cost items. A specific list of definitions was introduced to provide additional clarity about the precise information sought.

- Involving framework managers in the identification of potential interviewees, and recruiting at specific events, allowed a pre-qualification of interviewees to take place, in order to ensure that each had the necessary expertise to be able to respond to the questions.

Each interview had 2 distinct segments reflecting the two different types of information which were being sought. The first section of the interview took the form of an open-ended interview characterised by an interactive discussion which, while guided by an interview schedule was allowed to follow lines of discussion as they arose. The second part of the interview was more formal, akin to a standardised interview with a set list of questions with specific types of information sought. However, the complexity of the data sought still necessitated an element of probing and clarifying on the part of the researcher.

The outline interview schedule was developed based on the principles set out by Healey and Rawlinson [133]:

- Initial questions were open to encourage participants to open up and to allow the breadth and depth of their experience and expertise to be explored

- Sensitive questions about transaction costs were used last to allow more time to build up trust and confidence

- Opportunities were taken to summarise responses back to interviewees to test interpretation and clarify underlying meaning.

Table 4.6.3: Client interview schedule – initial questions

Question	**Purpose**
Can you tell me a bit about your organisation's experience of Energy Performance Contracts?	Opening discussion
Did you consider alternative procurement approaches for this work? What led you to choose EPC?	**Understand** why this procurement route was chosen? was this the only option?
Can you tell me a bit about how your organisation structures itself for these projects? What is your role? Who is in the core team? Do you buy in any external support?	Validity of responses, verify credentials of interviewee, understand team structure, understand size of team and use of external consultants
What methods did you use to evaluate bidders? proposals? Did you employ external consultants to support this?	**Understand** how much scrutiny is applied to proposals
What approach did you take to measuring and verifying energy savings? Did you employ external consultants to support this?	**Understand** approach to selection of M&V

Table 4.6.4: ESCO interview schedule - initial questions

Question	**Purpose**
Can you tell me a bit about your organisation's experience of Energy Performance Contracts?	Opening discussion
Can you tell me a bit about how your organisation structures itself for these projects? What is your role?	**Validity of responses**, verify credentials of interviewee, understand team structure
Which types of energy performance contract are you actively pursuing at the moment? Is there a reason you are not looking at the others?	Are some frameworks or types of project more popular than others? Should I also look at other contract models?**Validity of modelled options**
What tools do you use to calculate energy savings?(Engineering calculations, building energy modelling, previous experience and database information) Does that choice vary depending on the project?	Testing the assumption that a desire to reduce transaction costs leads to less detailed assessments of energy consumption / savings
Do you focus on particular technologies, or does it vary by project?	Generalisability of results and reliability of modelled options
Which risks do you think are hardest for ESCOs to manage? Do you take different risks on different technologies? How do you account for uncertainty?	Understanding approach to risk and what factors affect it. Validity of modelled options

Appendix C and Appendix D contain the supporting material used for the second part of the interviews with ESCOs and clients respectively. Experience from the feasibility stage interviews indicated that client representatives were often uncomfortable with allocating costs for particular elements of the transaction costs since they were unused to accounting for resources in monetary terms. As a result clients were asked to identify the number of person-hours required at each stage and a mid-scale salary cost was applied to calculate costs.

There is significant evidence from behavioural economics based on the work of Kahneman and Tversky [14] for the existence of anchoring and framing effects which would make interviewees more likely to select the particular values if presented with a range of options. To avoid this potential bias, interviewees were given a free choice for the values of different categories of transaction costs for each project. The sequence in which the case study projects are presented may also give rise to anchoring biases; with each project providing an anchor for the values of the next in the sequence. Care was taken to highlight the differences between projects in line with Chapman and Johnson's [134] findings that doing so would reduce the effects of anchoring.

4.7 Development of other model inputs

4.7.1 Installation Costs

Installation cost data was provided by a professional quantity surveyor based on the quantities prepared for the case study projects. Pricing was derived from tender returns for recent school projects. The location of the projects was assumed to be in London and the base date for prices was Q2 2016. The cost report can be found in appendix F.

4.7.2 Choice of discount rate

In order to ensure a consistent approach to project evaluation, the UK government has mandated a discount rate to be used in the majority of public sector projects, 3.5% [104]. This is the rate used to evaluate Client returns. Determination of the appropriate discount rate for ESCOs is a more subjective matter. Lind [135] suggests that for a commercial organisation the appropriate NPV would commonly represent the return forgone on alternative opportunities, which can be approximated by the gross profit margin. ESCO interview responses for the margin they would require for each project are shown in table 6.2.1. However, the range of values is extremely large and would have a very significant impact on the evaluation of the energy shortfall payments over the life of the project - after 4 years a payment discounted at 25% per annum would be worth less than half if it were discounted at 3.5%. Since the contractual structure in the current study means that all profit is received within the first 18 months of a project and only negative payments continue for the life of the project, this minimises the risk associated with the project and is in stark contrast with the evaluation which would result from the simple payback calculation. Berkovitch and Israel [136] report that techniques such as IRR, payback period and profitability index are more commonly used by firms in evaluating projects, and that while NPV is used by the majority of firms, it is considered a secondary technique. It is likely then that when results from an NPV analysis with a high discount rate conflict with those from a simple payback calculation with a zero discount rate, the results of the NPV analysis would be rejected. To address this conflict, and for consistency with the evaluation of client returns, the social discount rate, 3.5% was used to evaluate ESCO cash-flows.

4.7.3 Energy Saving Guarantees

Energy savings guarantees were equated to the expected energy saving. Most of the ESCOs interviewed described more nuanced approaches to the calculation of energy savings guarantees, with most suggesting that risk allowances would be applied to individual energy conservation measures rather than at a building level. However, they were not able to provide any details of this approach and in order to explore the impact of risk margins overall this was modelled as a single buffer in line with the practices described in the US by Goldman et al. [28] and Satchwell et al. [137].

In his analysis of risk allocation in PPP projects [138], Chang highlights that the “The issue of concern should be the mechanism through which the loss/gain will be allocated between parties after risks eventuate. An essential condition for ‘risk management responsibility’ to be trade-able is that one party’s promise of retaining responsibility can be enforced by a third party." Taken as a whole, the interview responses suggest that ESCOs seek to manage their risk exposure, where possible, through amendments and caveats to the contract.

4.8 Domain of applicability

The domain of applicability is the set of prescribed conditions for which the conceptual model has been tested. In addition to the obvious limitation of the model results to the context and case-study projects considered in this study, the domain of applicability is constrained by the set of assumptions which have been made in constructing the model. While a modelling study necessarily entails numerous simplifications, some are more significant than others. The principal modelling assumptions made in this study and their anticipated impact are as follows:

- **Fixed project timetable** Although Masten et al. [139, p. 9] report that "Where timely performance is critical, delay becomes a potentially effective strategy for exacting price concessions" and this is considered to be particularly true for the construction industry, this is not expected to be a significant concern for the projects considered in this study for two principal reasons:
  - neither client nor ESCO staff are typically engaged solely on the project, meaning that in the event of a delay staff resources are transferred to other projects and the impact of a delay is primarily experienced a change in the timing of costs rather than an increase in costs.
  - the installation of the ECMs is not a business critical activity, reducing the potential for hold-ups.
- **Fixed rate of return used for Net Present Value calculations** Returns for both Client and ESCO will be very sensitive to changes in the rate of return. This subject is discussed further in section 4.7.2.
- **Exclusion of maintenance and lifecycle replacement costs** Life cycle replacement costs have been excluded from this study on the grounds that the existing systems would also require replacement during the life of the projects studied. An earlier study [2], found that clients typically exclude lifecycle costs for project analyses.
- **Limits of stochastic approach** Although uncertain input parameters are selected in a stochastic manner in both energy models and the DSCF

model, they are not varied over time. This simplification has different consequences for different types of parameter:

- Characteristic parameters - parameters such as building fabric or systems characteristics are uncertain, but constant over the short term. Over longer time frames, these characteristics may degrade as a facility ages. Hoffman et al. highlight the lack of up to date information on degradation of savings over time [140]. and the implications of ignoring degradation are discussed in the context of sensitivity analysis in section 5.4.3.3.
- Stochastic parameters - parameters such as occupancy levels or operational settings which are inherently variable and may vary from year to year. In recent years, modelling of variable occupancy patterns has been the focus of considerable research attention, see for example Hong et al. [141]. However, these approaches require empirical data on which to base occupancy profiles, data which are not currently available for the schools sector. In addition, such approaches require considerable computational resources for a single model. Such resources were beyond the scope of this study when applied to the full range of buildings. In this study, the relevant output from the energy model is the aggregate annual energy consumption, making the in-year variability less significant. However, the overall impact of repeating a single profile for multiple years will be to exaggerate the effect of extreme profiles at both ends of the scale since these will be repeated for subsequent years and effects will not be balanced by less extreme profiles in subsequent years. Skumatz et al. [142] highlight that while performance degradation is a combination of both technical degradation and a "behavioural / operational component including the quality of use and quality of upkeep of the equipment" very little data is available on the second component. A further consequence of repeating energy savings pro-

files is that cash flows to Clients and ESCOs will be consistent year on year. The impact of this will be more pronounced in shared savings contracts than in the guaranteed savings mechanism modelled in this study, due to the potential in the shared savings mechanism for savings in early years to off-set later shortfalls.

- **ESCO decision to replace or pay** Clause 8 of Sch 2A of the RE:FIT contract [143] allows the ESCO to opt to replace under-performing equipment. However, as detailed in section 4.5.3, the scope of this study covers the range of outcomes arising aleatory and epistemic uncertainty and not from failures of equipment or installation. Consequently, the option to replace is not available.

4.9 Approach to sensitivity analysis

The rationale for a probabilistic study was set out in section 4.2 and section 5.4.2 discusses the procedure undertaken for screening energy model inputs for influential parameters. The method used for sensitivity analysis is consistent with these sections in using a global sensitivity analysis approach which allows all parameters to vary at once in order to map the full input space. The need for a method that allows for a non-linear model is underlined by the distribution of the energy model outputs 5.3.5.

In a Sobol' analysis, measures of importance can be calculated by considering the conditional variance of the model outputs, the amount by which model output variance is reduced as a result of fixing a particular input parameter. Saltelli and Annoni's [144] recipe for a Sobol' analysis is used where S_i, the first order sensitivity effect for model parameter i is given by:

$$S_i = \frac{V_{X_i}(E_{X_i}(Y|X_{\sim}i))}{V(Y)} \tag{4.1}$$

where:

X_i is the ith input parameter and $X_{\sim i}$ is the set of all parameters except X_i

V_{X_i} is the variance over all possible values of X_i

$Y|X_{\sim i}$ is the mean of Y taken over all possible values of $X_{\sim i}$ while keeping X_i fixed
V(Y) is the total unconditioned variance

S_{Ti}, the total sensitivity index, which includes all interactive effects is given by:

$$S_{Ti} = \frac{E_{X_i}(V_{X_i}(Y|X_{\sim i}))}{V(Y)} \tag{4.2}$$

4.10 Summary

This chapter has set out how a stochastic bi-partite discounted cash-flow model will be used to explore the four research hypotheses established in Chapter 3. The first part of the chapter detailed the model that has been developed based on the Greater London Assembly's RE:FIT programme. The need for an approach which encompasses uncertainty was highlighted.

The second part of the chapter focused on the method for collecting data on transaction costs, firstly by considering the types of transaction costs that might occur and secondly the process of eliciting data for transaction costs through semi-structured interviews with market participants.

The stochastic nature of this investigation entails a need to quantify and assess uncertainty in model inputs, and the approach to sensitivity analysis was also detailed in this chapter.

Chapter 5

Determining Production Costs

5.1 Overview

Chapter 4 set out the methods to be used to test the research hypotheses developed in chapter 3. Chapter 4 also sets out the context for energy performance contracting projects in the UK and considers the rationale for the selection of the schools sector as the focus of this study. The need to use hypothetical projects to allow collection of commercially-sensitive information was also highlighted in chapter 4. Using hypothetical projects has the benefit of allowing the freedom to construct cases which permit exploration of the dimensions of scale and scope. Project scale is considered by grouping different numbers of individual schools into a single project. Project scope is considered by applying two different sets of ECMs to each of these projects. A suite of 6 projects of varying scale and scope is thus created. Energy savings for each of these projects are calculated by modelling energy consumption of the underlying building archetypes, before and after installation of the ECMs.

The production cost for each project is defined as the cost of the energy services, since standing charges will apply both pre- and post- retrofit, these are ignored and the production cost is given by the energy consumed at the applied energy prices. This chapter is devoted to detailing the methods used to develop the energy consumption of the archetype buildings before and after retrofit. This chapter begins by confirming the project dimensions which must be defined in order to test the research hypotheses. The underlying building archetypes are detailed and the form of the Building Energy Simulation (BES) models used to calculate energy savings is discussed. A key focus of this chapter is on the treatment of uncertainty in BES models and the use of parameter screening to reduce dimensionality of the BES models and thus the computational load of calculating energy savings.

5.2 Testing the production cost hypotheses

Previous work [2] highlighted the variability of Priced energy savings as one of the most significant sources of uncertainty for all projects sizes and scopes. This indicated the requirement for dynamic building simulation in order to capture the effects of peak loads and changing patterns of occupation through the day. EnergyPlus [145] was selected as the appropriate simulation engine due to the ease of incorporation of parametric analysis, along with the availability of extensive documentation and support resources. Energyplus is widely used in research and industry and has been extensively tested. Designbuilder [146] was selected as the input interface due to the availability of training and academic licences.

Testing the research hypothesis means developing specific aspects of projects to allow comparisons to be made:

- Hypothesis 2

  Task complexity - the more accurately measurement and verification procedures can measure actual changes in energy consumption the more likely a project is to be viable. This hypothesis can be tested by comparing outcomes for clients and ESCOs under a range of different measurement and verification strategies.

- Hypothesis 3

  Technical potential for production cost savings - an EPC project is more likely to be viable when the range of energy conservation measures included is large. This hypothesis can be tested by considering alternative mixes of energy conservation measures.

- Hypothesis 4

  Aggregate production costs - increasing the size of a project by increasing the number of facilities included in it increases the likelihood of viability. This hypothesis can be tested by considering different numbers of sites, grouped together to form a single project.

5.2.1 Hypothesis 2 - task complexity

The literature review contained in chapter 2 identified the prevalence of the International Performance Measurement and Verification Protocol (IPMVP) as an approach for measuring and verifying savings. The IPMVP grew out the US energy performance contract industry standard [79]. Ten Donkelaar et al. [80] report its use in just under 50% of 100 European projects surveyed. However, Wang et al. [63, p. 80] draw attention to an important issue: "in a performance contract, verified savings can substantially deviate from actual savings". They highlight 4 categories of savings: projected, guaranteed, verified and actual; other authors [147, 130, for example] have typically considered verified and actual savings to be synonymous. However, the verified savings will be dependent on the measurement boundaries defined by the measurement and verification (M&V) strategy selected. IPMVP contains 4 distinct options for measuring savings, each with different measurement boundaries. Since many energy conservation measures may affect other building systems across these measurement boundaries, the total savings measured and thus guaranteed, may vary depending on the option selected.

Shonder and Slattery [130] report the following M&V strategy choices based on 139 projects in the USA as shown in table 5.2.1.

Although some commentators, for example, Walter et al. [148] suggest that the increasing availability of "interval data" will provide new opportunities for M&V, such data are based on whole building energy consumption. Since the low uptake of IPMVP option C is likely to be at least partly due to ESCO reluctance

Table 5.2.1: Relative popularity of each IPMVP M&V option

IPMVP Option	**Description** [66]	**% of project reporting its use** [130]
A	• Savings calculated separately for each measure • measurements taken for some variables • deemed (assumed) values used for other variables	65%
B	• savings calculated separately for each item • take measurements of all variables	18%
C	• determine savings using utility bills	4%
D	• determine savings using a calibrated computer model	13%

to accept exposure to changes in whole building energy consumption, it is not immediately evident that increased availability of interval data will resolve this concern. It is likely to be some time before such risks can be quantified and ESCOs become comfortable with their risk exposure, and so it is considered important to consider how existing M&V options can affect returns. Option D involves calibrating a simulation model to create the initial baseline. In the absence of actual consumption data against which a model could be calibrated this option was excluded from the study.

The modelling approach for each energy conservation measure under each measurement and verification approach is set out in table 5.2.2. For each ECM, both option A and option C measurement approaches exist. However, option B, field measurements of the isolated ECM is only practically possible for some ECMs.

Table 5.2.2: Measurement and verification option modelling approaches

Energy conservation measure	**Option A**	**Option B**	**Option C**
Lighting upgrade	Engineering calculation based on lighting power reduction and deemed no. run hours (2000) [149]	Lighting power consumption modelled in EnergyPlus	Whole building electricity consumption reduction in EnergyPlus
Heating controls	deemed saving of 8 % [150]	As option A	Whole building gas consumption reduction in EnergyPlus
Boiler replacement	Engineering calculation based on change in boiler efficiency and previous gas consumption	As option A	Whole building gas consumption reduction in EnergyPlus
Pipe and flange insulation	Deemed saving of 8% [151]	As option A	Whole building gas consumption reduction in EnergyPlus
Draught stripping	Deemed saving of 4% assumed	As option A	Whole building gas consumption reduction in EnergyPlus

5.2.2 Hypothesis 3 - technical potential for production cost savings

Two options are considered for project scope - retrofitting with 2 energy conservation measures (a lighting upgrade and replacement of heating controls) and with 5 energy conservation measures (lighting upgrade, replacement of heating controls, boiler replacement, pipe and flange insulation and draught-stripping). These energy conservation measures (ECMs) were selected from analysis of the most prevalent energy conservation measures in the Greater London Assembly's RE:FIT programme case study projects [20] and comparison with the Department for Business, Energy and Industrial Strategy's Building Energy Efficiency Survey [152] confirms these as the most probable ECMs for schools energy efficiency upgrades. The grouping of the measures was tested with framework managers who confirmed that they would consider the 2 project options to be viable. Building fabric measures are not included as payback periods for these measures typically extend beyond the 8 year threshold for Salix funding [125]. Table 5.2.3 explains how the ECMs are modelled and revised ranges for the parameters affected by each energy conservation measure can be found in Appendix E.

Table 5.2.3: Energy conservation measures modelling approaches

Energy conservation measure	**Definition**	**Modelling approach**
Lighting upgrade	Replacement of luminaires and installation of automatic lighting controls	Reduction in lighting gain and adjustment of lighting schedules to reflect occupancy profile post intervention
Heating controls	Installation of local heating controls (ie. thermostatic radiator valves)	Reduction in set point temperatures
Boiler replacement	Replacement of existing boiler installation with new	Increased boiler efficiency, alternative boiler efficiency curve, reduced part-load ratio
Pipe and flange insulation	Exposed pipe in plant room replaced with insulated pipe	Change in construction of pipe to insulated pipe
Draught stripping	Installation of draught strips to windows and doors and sealing of building penetrations	Reduction in air infiltration rate

5.2.3 Hypothesis 4 - aggregate production costs

Hong's [153] analysis of a large set of school DEC data identified the need to dis-aggregate schools into two categories, primary (pupils aged 4 - 11) and secondary (pupils aged 11 - 16/18). Consequently an archetype was selected for each of these two categories. While there is considerable diversity in the school estate, school building in the UK has tended to occur in waves, driven by the age of existing buildings but also by societal changes and changes in expectations of education [154]. This suggests that it would be possible to break the primary and secondary school categories down further into "clusters" with fairly homogeneous characteristics. This approach has been used in housing stock modelling [114] where the aim has been to characterise an entire estate. Since the aim of this study is to consider impacts of increasing scale rather than across an entire estate, a single archetype was selected for each of the two categories of schools. By limiting the study to 2 archetypes, the impact of different forms of construction and different building geometries are excluded from this study, which may have implications for the generalisability of conclusions. In particular, a more heterogeneous estate would result in a more balanced set of risks as different buildings would have different ECMs and different failure modes. Figure 5.2.1 illustrates the ECMs on the cross-section of a primary school.

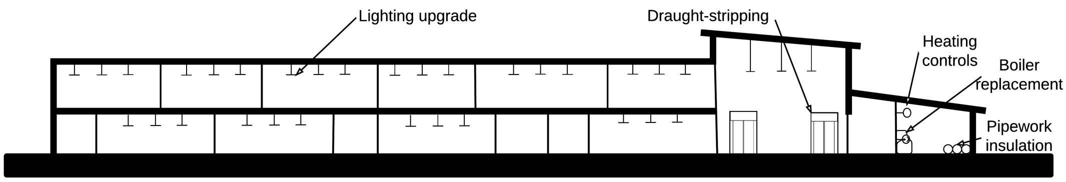


Figure 5.2.1: Energy conservation measures (ECMs) considered

Three alternative project scales were considered:

- small – 6 primary schools
- medium – 10 primary schools and 2 secondary schools
- large – 20 primary schools and 4 secondary schools

5.3 Building archetypes

London was selected as the location for the projects due to the existence of the GLA's RE:FIT programme which means that a number of energy performance contracts have already been undertaken in schools. There are 1630 primary schools in London for which data is available, of these 52% have between 210 and 420 pupils with a median of 384 [155] equating to two classes or forms of entry (FE) in each year, each with a maximum of 30 pupils. As a result, the Department for Education (DfE)'s baseline design for a 2FE primary school was selected as the basis of a primary school exemplar [156]. The occupancy density of this design is approximately 4 m^2 per person, which is higher than the median of 5 m^2 per person reported for schools in the Department for Business Energy and Industrial Strategy (BEIS)'s Building Energy Efficiency Survey [152], reflecting the fact that the archetype has been designed for current education practice.

Much less information is available on secondary schools as they are more likely to be Academies and thus exempt from the reporting requirements. The BEIS data suggests 33% of secondary schools have pupil numbers in the 1000 to 1499 range and a median occupancy level of 8m^2 per person, which compares with 6.2m^2 per person for the archetype secondary school. Since the DfE baseline designs were developed with the aim of reducing the overall floor area of the school it is likely that the difference in area will be due to reductions in circulation spaces rather than reductions in teaching space, meaning that the impact on overall energy consumption will be lower than the headline figure suggests.

5.3.1 Modelling the archetype buildings

The two school archetypes were modelled in version 8.3.0 of EnergyPlus [145]. A key advantage of using EnergyPlus is its editable input file which allows automatic generation of multiple input files using different parameter sets. After creating initial building models in in DesignBuilder, the input files were tagged by replacing parameter values with variable names. Matlab [120] was used to generate sets of values for each variable parameter based on Sobol' sampling as described in 5.4.2. A series of input files were created by successively substituting the parameter value name tags in the base input file with the sets of sampled values. EnergyPlus simulations were then executed with 6 time-steps per hour for a full annual simulation using the UCL Legion high performance computing facility. The distributions from which variable parameters were sampled are detailed in Appendix B. EnergyPlus contains a wide variety of alternative sub-models for many different calculation types and the choice of sub-models has potentially significant implications for calculation results. Evaluation of the impact of each sub-model choice was beyond the scope of the resources available for this current study, with one exception which is discussed in section 5.3.4. Since the outputs of interest are annual consumption of gas and electricity, the implications of the choice of sub-models are likely to be less significant than for a finer-grained analysis.

Legislative requirements mean that teaching time in schools is tightly defined, however, patterns of building occupation and use are poorly understood outside core school hours, for example, Burman's [157] analysis of 5 secondary school buildings found 50% of energy was used outside of teaching hours. Operating schedules incorporate wide variations to reflect this.

5.3.2 Primary school energy model geometry and zoning

The DFE primary school archetype comprises 3 adjoining blocks, a single storey kitchen and plant block, which is adjacent to a double height assembly/gym hall, which is next to a 2 storey classroom block. The rendered DesignBuilder model can be seen in figure 5.3.1. To reduce model complexity, adjacent areas with equivalent orientation, functions and operational schedules are modelled as single zones. This results in a total of 33 zones, the thermal mass of the missing partitions was not included as this was not expected to have a significant effect. The ZoneVentilation:DesignFlowRate model is used with flow rates as detailed in appendix B.

Ventilation is single-sided with trickle vents and opening windows used to bring untreated outside air into the building.

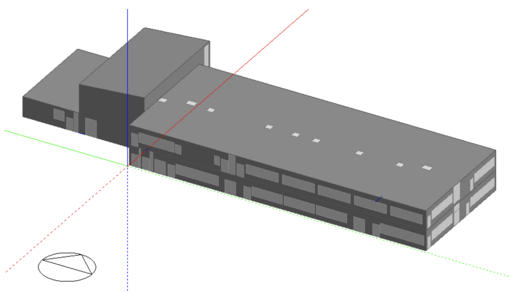


Figure 5.3.1: Primary school energy model

5.3.3 Secondary school energy model geometry and zoning

The procedure used to create the primary school energy model was replicated to create the secondary school energy model. This design comprises a predominantly three-storey central block containing the largest volume spaces in the school with two three-storey wings of classrooms and an adjacent 2.5 storey height sports hall block. The two teaching block wings and the main block have a double-loaded corridor format with a full height atrium in each of the three principal circulation spaces. Ventilation is double-sided, with trickle vents and opening windows used to bring untreated outside air into the building from the external façade with vents in the corridor wall leading to atrium spaces with vents at roof level. No mechanical assistance is provided and ventilation relies on the stack effect. The ZoneVentilation:DesignFlowRate model is used with flow rates as detailed in 5.4. The secondary school model comprises a total of 76 zones as a result of combining adjacent areas with similar functions, orientation and occupancy schedules into a single zone.

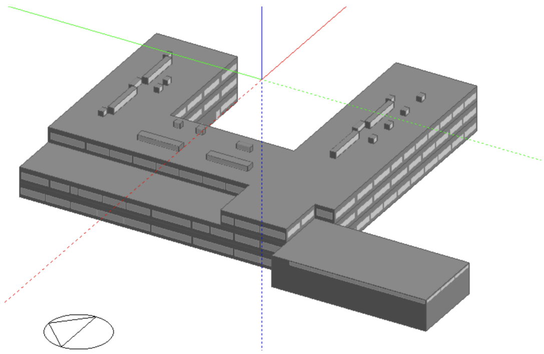


Figure 5.3.2: Secondary school energy model

5.3.4 Building systems

Display Energy Certificate (DEC) data presented in Hong [153] show that only 1.2% of schools and seasonal use public buildings are electrically heated and that of the non-electrically heated schools buildings 96% of primary schools and 87% of secondary schools are characterised as being natural ventilated. The two archetype designs are thus modelled as having gas-fired boilers serving water-filled radiators with ventilation supplied through vents and opening windows.

The layout of the heating system used in both archetypes is shown in figure 5.3.3.

Heat emitters are modelled using the ZoneHVAC:Baseboard:Convective:Water object; this ignores any radiative component of heat transfer. Using this object results in faster simulation runs as EnergyPlus does not need to calculate the radiative heat transfer to each surface in each time step. The complex geometry of some spaces means that this simplification more than halves simulation times from approximately 30 minutes for a single secondary school model to 13 minutes. This assumption was tested by using a categorical variable for calculation method and including the impact of calculation method in the sensitivity analysis.

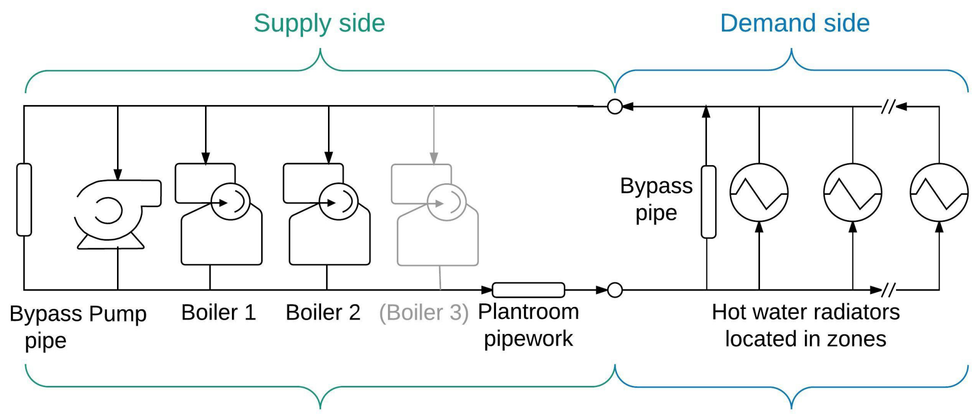
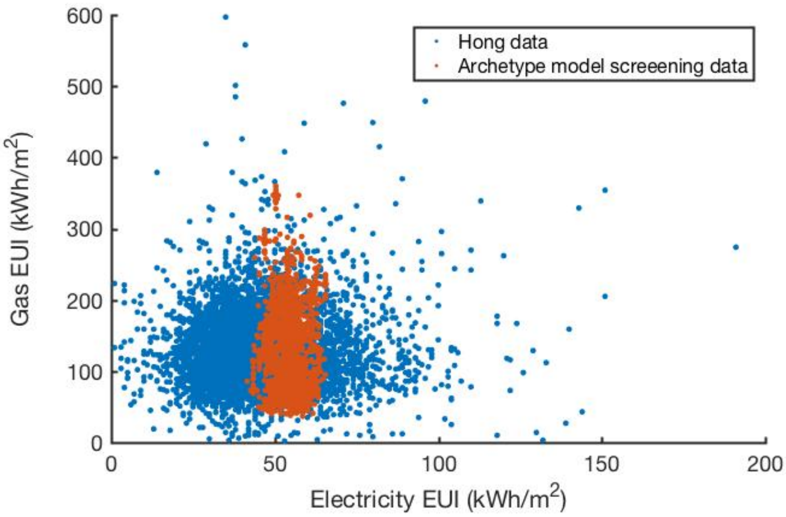


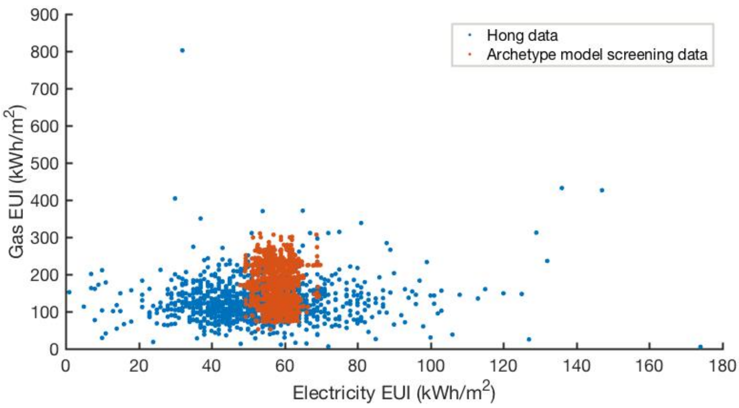
Figure 5.3.3: Heating system layout for both building archetypes

5.3.5 Model validation

The case study models are based on template school designs and not actual buildings, consequently they cannot be validated against measured data. Figure 5.3.4 shows the set of comparisons of the normalised output from the model validation runs against Hong's DEC data [153] data. Since Hong's data set included the actual energy consumption of the buildings it includes the effects of operation and management on energy consumption and so is an appropriate comparator. Hong's data set contains a much higher number of data points for primary schools than for secondary schools. Although comparison with Hong's Display Energy Certificate data set is complicated by a number of outliers in in his data, figure 5.3.4 indicates that both archetype models represent a set of buildings within the expected range. For both building archetypes, electricity consumption is more tightly clustered than the gas, this is more pronounced for the secondary school model. Figure 5.3.4 confirms that the archetype models represent plausible sets of buildings within the school estate and are thus suitable for the purposes of this study. However, the overall study results need to be interpreted with caution given the over-weighting of high gas consuming buildings with respect to the broader data set.



(a) Primary school



(b) Secondary school

Figure 5.3.4: Comparison with Hong's DEC data set

The sensitivity analysis described in section 5.4.1 was also used to sense-check the underlying energy models. Interrogation of the sensitivity analysis results for plausible mechanisms driving the influence of particular parameters allowed the identification and correction of a number of modelling errors.

5.4 Dealing with uncertainty

As Monari and Strachan [158] highlight, building energy simulation (BES) models are inherently complex: "BES models have complicated structures consisting of many in-built sub-models that attempt to represent the physical reality and large numbers of input parameters". In particular, BES models are fundamentally non-linear, comprising a number of different mechanisms for heat transfer, which means that in different locations in the input space, different mechanisms may dominate; for example, window-opening regimes determine whether heat loss from the building is predominantly due to conduction losses through the building fabric, or ventilation losses. Booth et al. [114] add model uncertainty to the aleatory and epistemic uncertainty categories identified by Helton [113] and discussed in section 4.2. This echoes the concerns raised by Monari and Strachan [158] regarding the importance of the choice of submodel within an overall BES. Reddy et al. [159] relate the concerns raised by Oreskes et al. [115] to building energy simulations, noting that building energy simulation models are inevitably under-determined, comprising as they do many thousands of input parameters even for a simple building model. As a consequence, BES of a complex, multi-zoned building will involve a very large number of potential variables, including some which will be multi-dimensional due to variation over time. The high-dimensionality of the input space for a BES as a result of the very large number of uncertain input parameters makes models computationally very demanding to evaluate over the full range of model inputs. Global sensitivity analysis screening methods offer a means of reducing the dimensionality of the model without sacrificing the accuracy of the results. In particular, the Elementary Effects method, originally formulated by Morris [160] has been extensively used within the BES field for screening purposes [161, 162, 74, 163, 164, for example]. This study follows these approaches using a modified version of Morris's elementary effects method to identify the most influential parameters in the BES model allowing its dimensionality to be reduced when exploring the impact of energy conservation measures (ECMs). The screening process and its results are set out in the following sections.

5.4.1 Identifying potentially influential parameters

A key constraint in any sensitivity analysis, even those used for screening purposes, is the computational burden of defining the uncertainties associated with each variable parameter. Consequently, although not explicitly stated in the literature, screening typically involves a preparatory qualitative phase based on literature review. It should be noted that this phase necessarily sets the bounds for subsequent phases since a parameter can only be identified as influential if it was not fixed and only the parameters which are explicitly selected as variable will not be fixed. It is important to note that it is always possible that potentially influential parameters have been inadvertently excluded from the analysis at this preparatory stage.

Since EPCs typically take place in a commercial setting where cost and time pressures place significant constraints on the amount of information that can be collected about an existing building and its operation, it is anticipated that epistemic uncertainties will dominate the BES model.

A long-list of variables was created from a review of the literature pertaining to the identification of significant variables in building energy models [162, 161, 165, 166].

- Fabric – thermal properties of the building fabric
- Systems – efficiency of the building systems
- Operation – temperatures and hours of operation, ventilation strategy
- Occupancy – numbers of occupants and hours of occupancy

All parameters are treated as univariate, that is fixed at the point at which the model is run. While some parameters such as occupancy levels are multidimensional in reality, the computational demands of modelling the temporal variations are beyond the scope of this study. In a comparison of differing approaches to parameterisation of occupancy effects, Ward et al. [167] found NCM data resulted in an overestimation of midweek loads and an under-estimation of weekend loads in a university office building. However, these effects would be expected to be significantly lower in a school environment where the occupancy schedule is more strictly defined. Further, Ward et al. note that where aggregate data are required (as is the case in the current study), a deterministic profile may be appropriate provided the full range of possible results is considered.

Another category of parameter which could exhibit dynamic variation over time is the performance of the installed energy conservation measures themselves. While demand-side management programmes operating in the USA typically make allowance for the persistence of savings over time, Hoffman et al. [168] found a wide divergence between values used and a lack of evidence to support the selection of a particular value.

Building geometry, orientation and location were identified as potentially important parameters but excluded as they are capable of being well defined, and thus make little contribution to the uncertainty around energy consumption pre- and post retrofit. The impact of climate was tested with the inclusion of a binary variable which allocated input data sets to one of two weather files based on the randomly sampled variable. Results for gas consumption were normalised for heating degree days using the procedure set out by Hong [153, p. 113] since this is a standard contractual adjustment.

Ranges and distributions for each parameter were identified from the literature, appendix B sets out the individual parameters and the data sources for each. Three types of probability distribution were used for the parameters in the study:

- Normal distributions were used for parameters where uncertainty is dominated by variation in physical characteristics and the spread is small relative to value. For example, boiler efficiency, infiltration, lighting gains (post-retrofit)

- Triangular distributions were used for parameters where uncertainty was dominated by lack of knowledge of existing installed components or patterns of use and the spread is large relative to value since using a normal distribution would underweight extreme values and result in impossible values. For example: lighting gains (pre-retrofit), equipment gains, on/off times for lighting, equipment, occupancy or heating schedules

- Uniform distributions were used for parameters where information concerning the distribution of parameter values was not available or the parameter is a user-defined setting and all values are assumed to be equally likely. For example, domestic hot water loop outlet temperature.

A number of simplifying assumptions were made, these are detailed in appendix B.

A second binary variable was introduced to evaluate the choice of heating model, simulation sets were assigned to either a convective only heating model or to a radiant-convective model based on the randomly sampled variable.

5.4.2 Parameter screening

The Elementary Effects approach creates a series of sets of input parameters where each pair of sets differs in only one input parameter, consequently the variation in model output between the sets of input parameters is only due to the varied parameter. The Elementary Effect (EE) is the normalised difference in output resulting from the two sets of input parameters. A series of k+1 sets of input parameters is required to give one estimate of EE for each input parameter where k is the number of input parameters. Notation used throughout follows Campolongo et al. [169].

$$EE_i = \left| \frac{y(x_i^{(u)} x_{\sim i}^{(u)}) - y(x_i^{(v)} x_{\sim i}^{(u)})}{(x_i^{(u)} - x_i^{(v)})} \right| \tag{5.1}$$

where:

EE_i is the elementary effect of the ith parameter

$y(x_i^{(u)}x_{\sim i}^{(u)}) - y(x_i^{(v)}x_{\sim i}^{(u)})$ is the difference in output resulting from input vectors u and v of the output parameters where parameter i is the parameter being held constant

$x_i^{(u)} - x_i^{(v)}$ is the difference in the input vectors

The procedure is repeated a number of times to give a number of estimates for EE for each parameter. In his original work, Morris used the mean and the standard deviation of the estimates for each parameter to characterise the sensitivity of the model output to changes in that parameter. Two key concerns regarding the original Morris Method have been addressed in more recent work. The first, the potential for the estimates of opposite sign to cancel each other out, resulting in an influential factor being incorrectly classified as non-influential, was addressed by taking the mean of the absolute values of measured variance, μ^* [170]. Where

$$\mu_i* = \frac{1}{n}\sum_{j=1}^{n}\left|EE_i^j\right| \tag{5.2}$$

The second concern, that the coarse search pattern proposed with the original "winding stairs" design leads to inadequate coverage of the input space is addressed through the application of a radial sampling design [169] this is the form used in equation 5.1.

Sobol' sequences were used to generate samples from the distribution U(0,1) for each parameter using the sobolset routine in Matlab based on [171]. Sobol' sequences were created to systematically fill the input space based on previously selected points and so are not strictly random numbers but have been demonstrated to provide better coverage of the input space than other sampling strategies such as random numbers or Latin Hypercube sampling, [172]. The procedure set out in [169] was used to generate 8500 samples for a radial sampling strategy for the primary school (100 estimates for each variable parameter) and 8800 for the secondary school model (100 estimates for each variable parameter). Each sample is mapped to the input space of the relevant parameter using the inverse of the cumulative probability density function (CDF) for that parameter since the CDF is by definition a continuous function between zero and one.

The original formulation of the Morris method uses a uniform distribution for all variable parameters which would tend to over-weight extreme values leading to type I errors where non-influential parameters are identified as influential. In the modified Morris method used in this study, normal and triangular distributions were used in addition to uniform distributions, as discussed in section 5.4.1.

The number of runs required to give good coverage of the input space was assumed to be the number of estimates required for convergence multiplied by the number of influential parameters. This result was then validated according to the procedure for screening validation set out by [173]: An additional set of model inputs is generated, $\{y \mid \overline{X_0} \mid\}$ where the input parameters in X_0 are fixed while the remaining parameters take the values defined in the initial sampling process. Empirical Cumulative Distribution Functions (CDFs) are then calculated from the conditional and unconditional model outputs and a two-sample Kolmogorov-Smirnov (KS) statistic is used to estimate the discrepancy between the two sets of outputs.

5.4.3 Screening results

5.4.3.1 Primary school screening results

Gas consumption results were normalised according to heating degree days as set out in 5.3.5 above, since this is an industry standard adjustment. The output of interest is the remaining variation after the adjustment. When sampling from a normal distribution, there is the potential for impossible values to be selected which result in a failed run. Where the failed run forms the base parameter set for a set of estimates, each run which is associated with that base parameter set must also be treated as a failed run. Failed runs are replaced with dummy values which are removed in the final calculations.

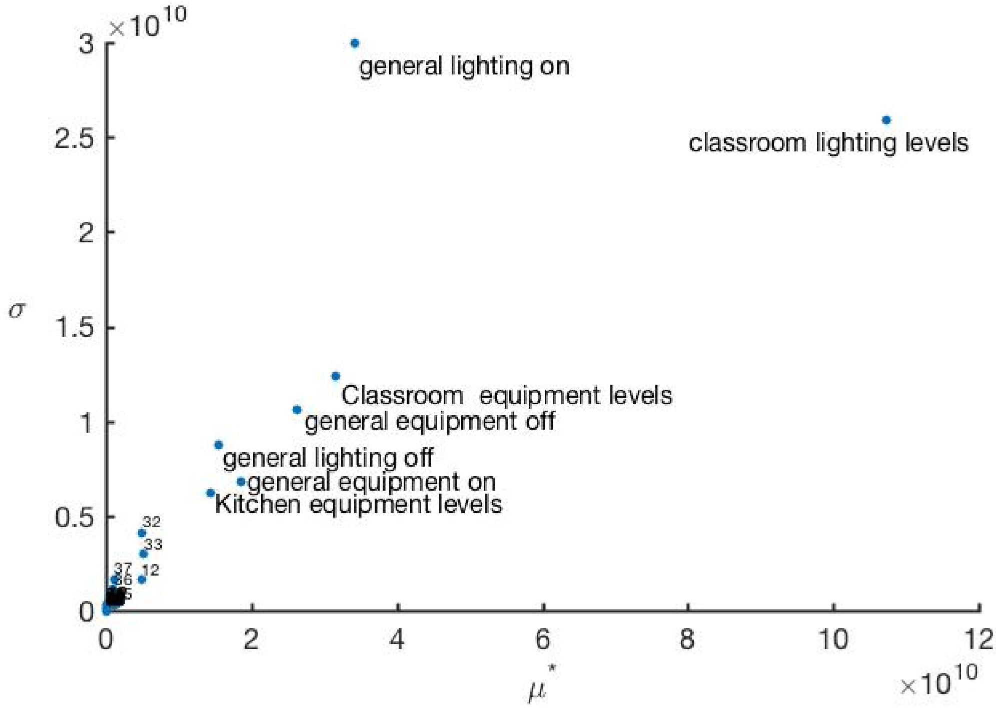


Figure 5.4.1: Primary School - elementary effects of each parameter on annual electricity consumption

Figures 5.4.1 and 5.4.2 show the mean elementary effect for each parameter, plotted against the standard deviation for each elementary effect. While the elementary effect shows the relative sensitivity of the output to the input parameter, the standard deviation shows which parameters are most strongly interactive. As this is semi-quantitative method, a graphical approach to identifying the most influential parameters was preferred.

The number of iterations required to reach a stable ranking of parameters gives a strong indication of the minimum number of samples required for adequate coverage of the input space. Figures 5.4.7 and 5.4.8 suggest that approximately 55 samples are required per varying parameter to achieve a stable separation into sets of influential and non-influential parameters, the same number of iterations was used for the primary school model although figure 5.4.3 indicates earlier convergence into two sets.

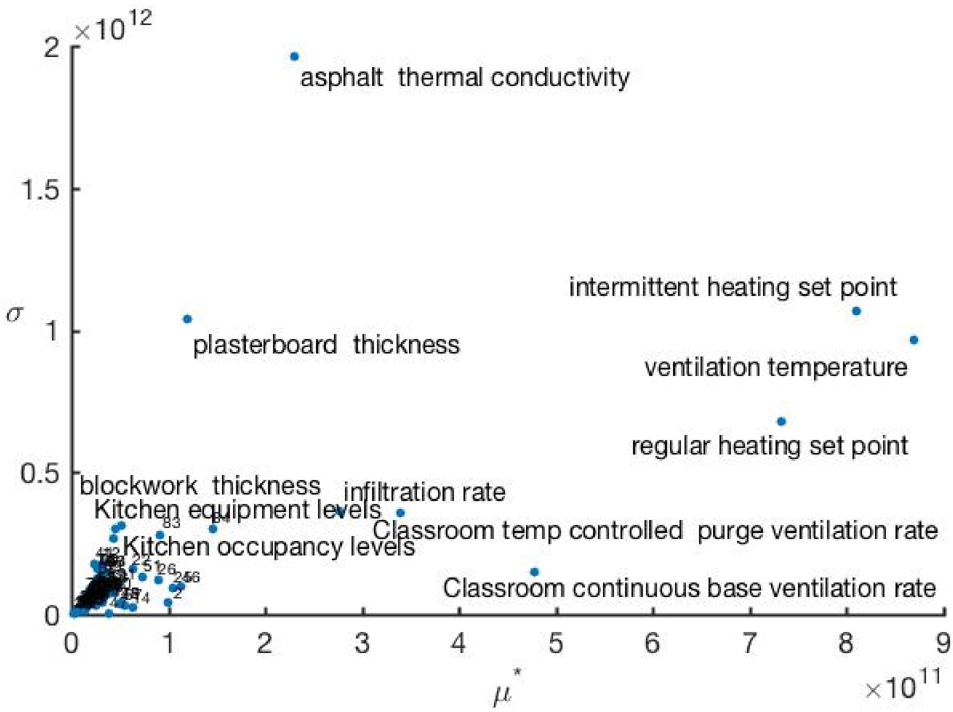


Figure 5.4.2: Primary School - elementary effects of each parameter on annual gas consumption

Screening results for gas consumption for the primary school presented in figure 5.4.2 indicate that asphalt thermal conductivity is, unexpectedly, an influential parameter. Inspection of the individual estimates suggests that this is due to a single pair of model results, the effect of which decreases as subsequent estimates are added. Repeating the sensitivity analysis does not repeat this result. However, the inclusion of asphalt thermal conductivity as an influential parameter when it is not influential only has the effect of increasing the number of model runs required.

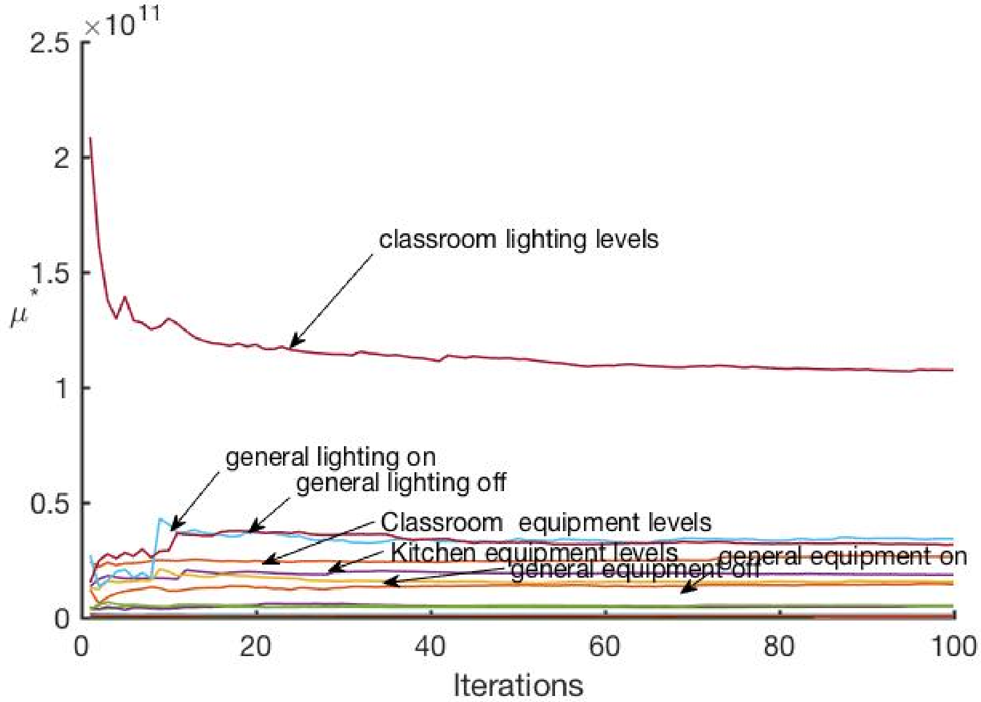


Figure 5.4.3: Primary school - effect of adding successive estimates of elementary effect on annual electricity consumption

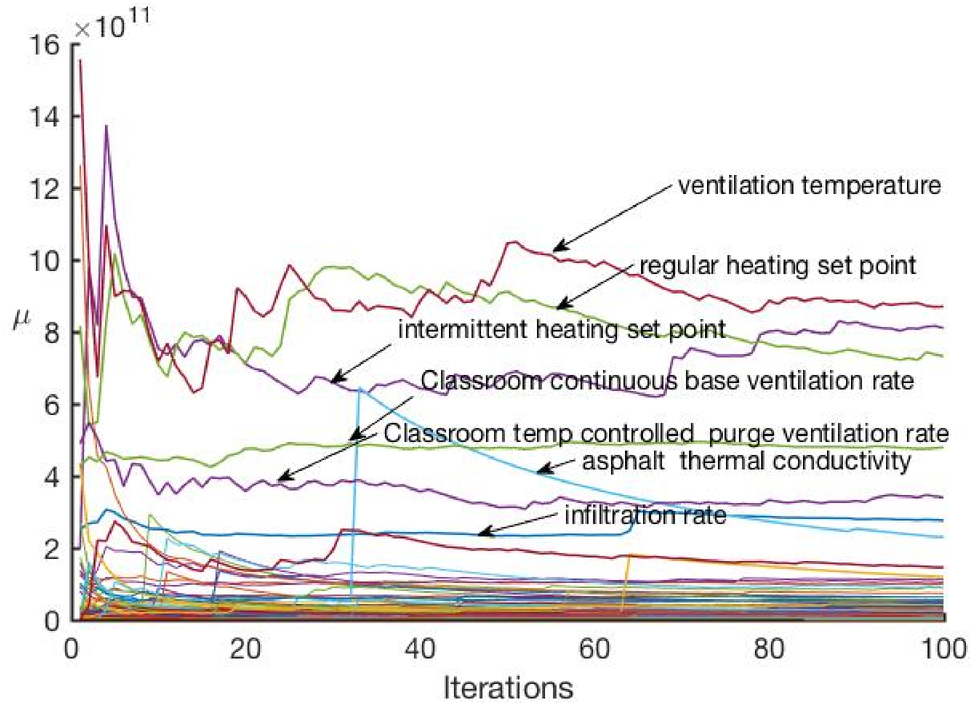


Figure 5.4.4: Primary school - effect of adding successive estimates of elementary effect on annual gas consumption

5.4.3.2 Secondary school screening results

Since local cooling is included in practical and ICT areas in the secondary school the number of influential parameters identified for the annual electricity consumption is higher than in the primary school model which contains no cooling. Figures 5.4.5 and 5.4.6 show the mean and standard deviation of the elementary effects for each parameter on annual electricity and gas consumption respectively, indicating a total of 25 influential parameters. Figures 5.4.7 and

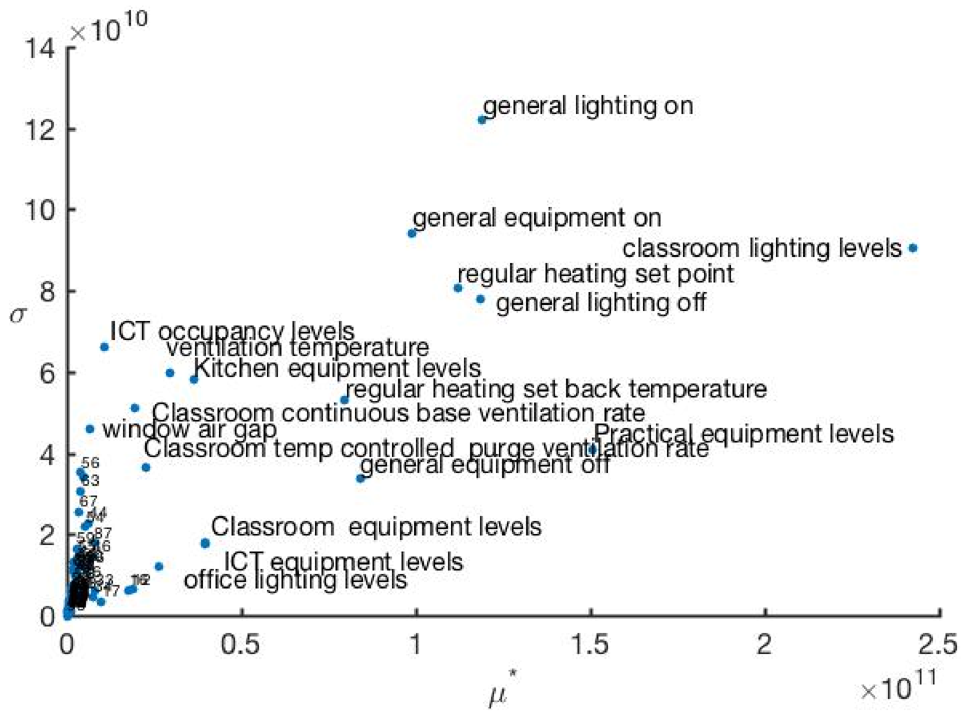


Figure 5.4.5: Secondary School – elementary effects of each parameter on annual electricity consumption

5.4.8 indicate that, as with the primary school model, about 55 samples per varying parameter should result in adequate coverage of the input space.

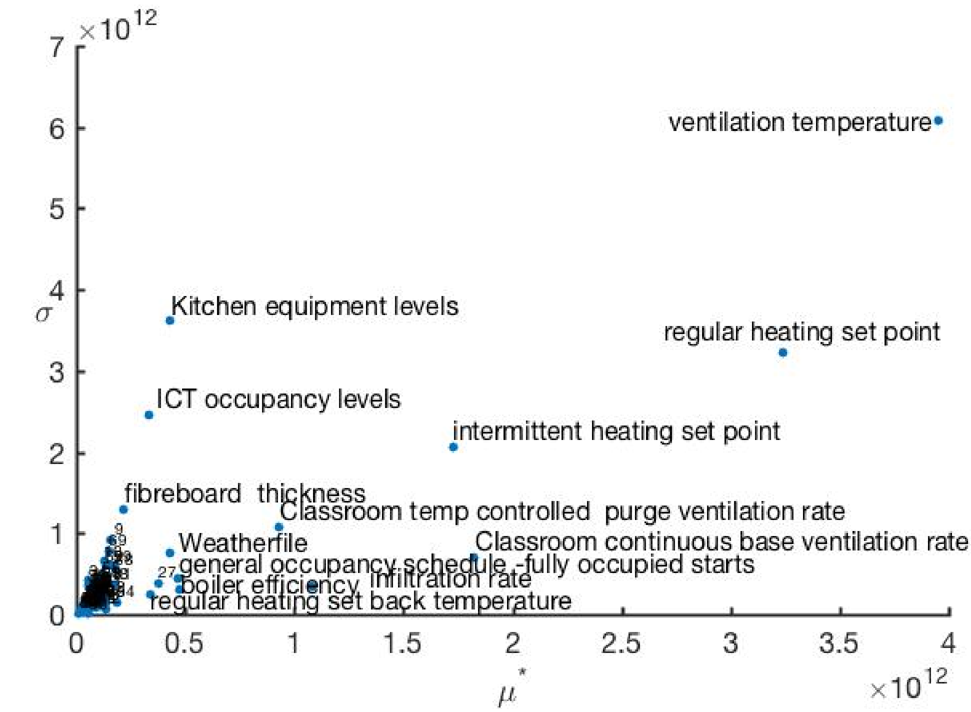


Figure 5.4.6: Secondary School -elementary effects of each parameter on annual gas consumption

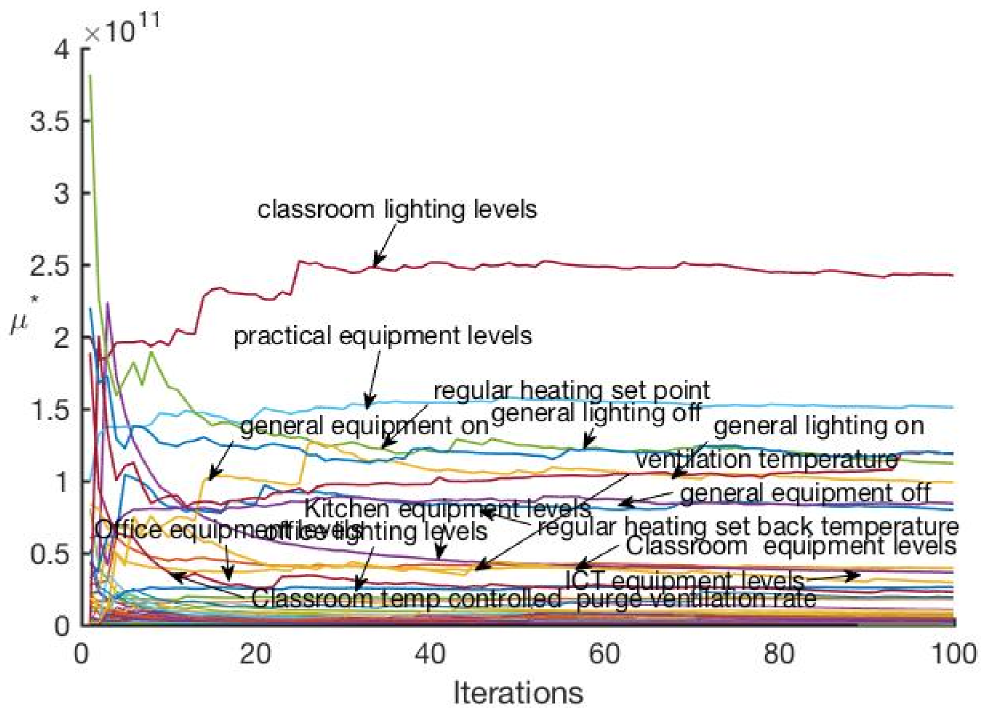


Figure 5.4.7: Secondary school - effect of adding successive estimates of elementary effect on annual electricity consumption

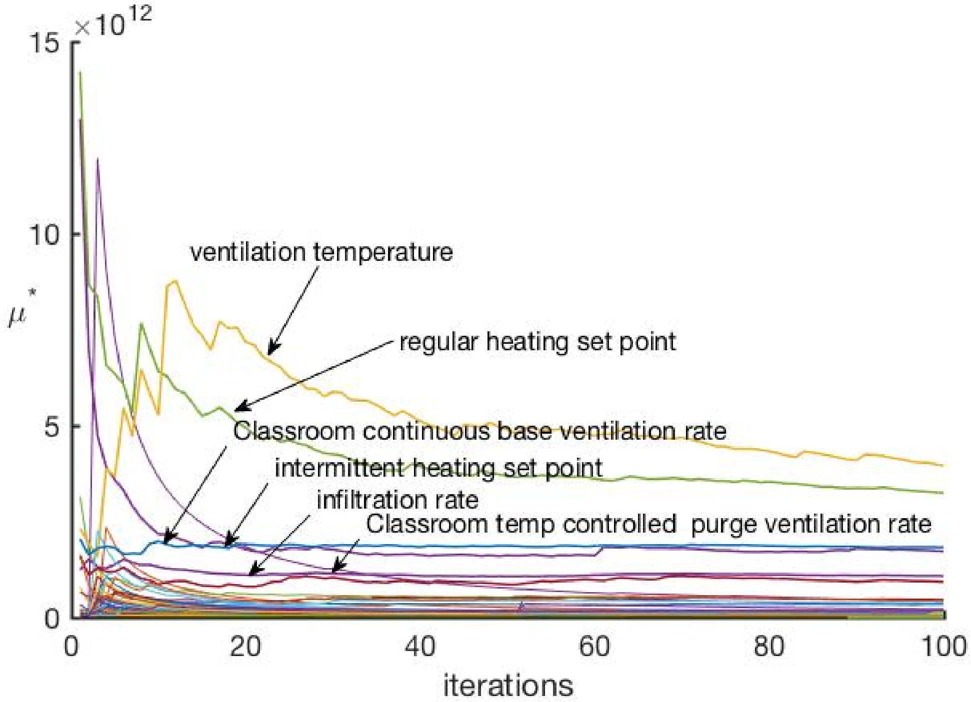


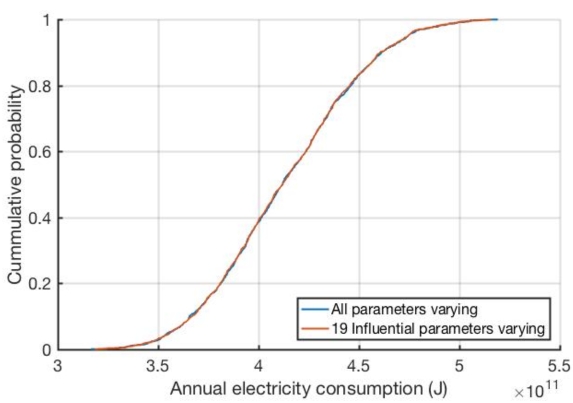
Figure 5.4.8: Secondary school - effect of adding successive estimates of elementary effect on annual gas consumption

5.4.3.3 Validation of screening results

The screening process was undertaken to enable the dimensionality of the models to be reduced without sacrificing the accuracy of the model output. To validate the results of the screening process a set of samples with all parameters varying was generated, this set was replicated to form a second set of samples in which the non-influential samples were fixed at their mean values [161] A two-sample Kolmogorov-Smirnoff test was selected to test the 'goodness-of-fit' of the two distributions of outputs. The Kolmogorov-Smirnoff test has the advantage of being non-parametric and by avoiding grouping samples there is no loss of information [174]. The two distributions were compared at the 5% level, meaning that a deviation between the two distributions of more than 5% would result in the the screening results being rejected. Cumulative distribution plots for model outputs for the reduced and full models are shown in figure 5.4.9.

Table 5.4.1: Influential parameters for primary and secondary school models

Primary School Influential parameters	**Secondary School Influential parameters**
Classroom occupancy levels	Toilet occupancy levels
Classroom equipment levels	Classroom equipment levels
Kitchen equipment levels	ICT equipment levels
Classroom lighting levels	Kitchen equipment levels
Intermittent heating set point	Office equipment levels
Regular heating set point	Practical equipment levels
General occupancy schedule – fully occupied starts	Classroom lighting levels
General equipment on	Office lighting levels
General equipment off	Hall lighting levels
General lighting on	Ancillary lighting levels
General lighting off	Intermittent heating set point
Ventilation temperature	Regular heating set point
Infiltration rate	Regular heating set back temperature
Boiler efficiency	General occupancy schedule – fully occupied starts
Asphalt thermal conductivity	General occupancy schedule – partially occupied pm starts
Plasterboard thickness	General equipment on
Classroom temp controlled purge ventilation rate	General equipment off
Classroom continuous base ventilation rate	General lighting on
	General lighting off
	Ventilation temperature
	Infiltration rate
	Boiler efficiency
	Window air gap
	Insulation urea foam thermal conductivity
	Glass thickness
	Classroom temp controlled purge ventilation rate
	Classroom continuous base ventilation rate



The screening validation shown in figure 5.4.9 shows good agreement between the outputs for the full and reduced models with the exception of the secondary school model gas consumption which fails the KS-test at the 5% level. Excluding weather variation from the results by repeating the analysis with results of only one weather file shows good agreement and satisfies the KS-test as shown in figure 5.4.10.

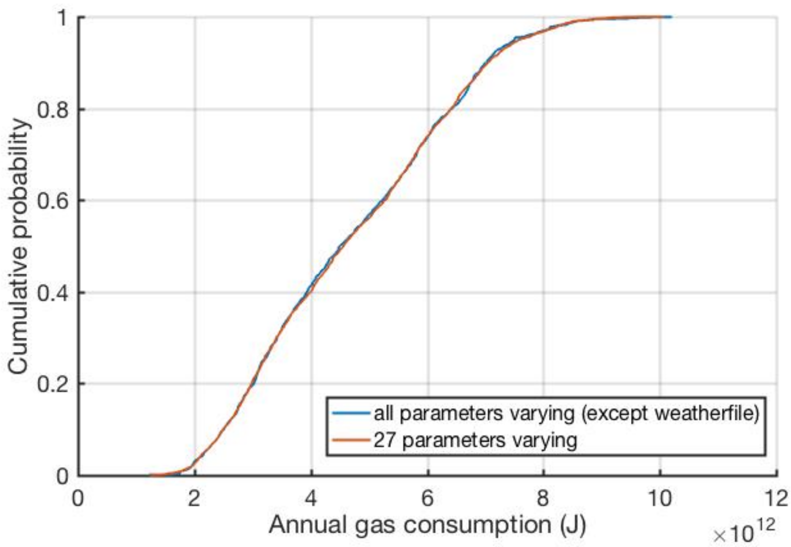


Figure 5.4.10: Secondary school - reduced and full model comparison with weather file variation excluded

This result indicates that adjusting for temperature using the heating degree day adjustment described in section 5.3.5 above is inadequate to normalise the impact of weather variation on energy consumption. This is in line with Kalamees et al.'s [76] assertions that windspeed and solar radiation will also affect both heating and cooling energy and relative humidity will affect cooling energy. Since figure 5.4.9 indicates better agreement for electricity consumption (which includes cooling energy) than for gas consumption (which is dominated by heating energy), it is likely that the effect observed is due to windspeed, which would have a greater impact on infiltration in the 3-storey secondary school building than than the 2-storey primary school building but further work would be necessary to verify this.

5.5 Energy prices

Energy prices are based on the retail prices for services in the Department for Business, Energy and Industrial Strategy's 2016 energy price projections [175] which is the latest set of projections available. As these projections represent 3 unique trajectories, these were modelled as 3 separate scenarios. These prices exclude VAT but include Climate Change Levy. Standing charges were excluded from the analysis as they would be the same pre- and post-retrofit.

Since monthly energy prices were required, it was assumed that a constant price applied throughout the year, rising annually on 1st April.

The price projections extend to 2035. In the event that a project has a payback period that extends beyond this, the model assumes no growth in fuel prices in real terms Although this is a crude assumption, the effect of changes in price post 2035 are likely to be very small due to the discount rate of 3.5% applied in the NPV calculations.

5.6 Summary

This chapter detailed the approach to developing two building archetypes to which a range of energy conservation measures are applied in order to calculate energy consumption pre- and post-retrofit. These energy savings are combined with utility prices to create distributions of production costs, which form inputs to the DSCF model described in chapter 4. Generating probability distributions of energy savings for the two archetype buildings is a computationally intensive process and this chapter also explained the sensitivity analysis process which was used to reduce model dimensionality to address this.

Chapter 6

The Impact of Transaction Costs on Financial Returns

6.1 Overview

Transaction costs were identified as a key barrier to growth of the energy performance contracting market by a number of commentators, as discussed in section 2.3.1. The first of the four research hypotheses set out in chapter 3 related transaction costs to market competitiveness by stating that a more competitive market will result in lower transaction costs and thus increase the viability of EPC projects. This chapter begins by presenting the transaction cost data collected through interviews with a range of Clients and ESCOs. The challenges of data collection and limitations of the data are also discussed. The second part of this chapter discusses the influence on transaction costs on returns for Clients and ESCOs and considers the evidence for the first research hypothesis.

6.2 Collecting transaction cost data

Chapter 4 set out the approach to developing transaction cost inputs through semi-structured interviews with a range of clients and ESCOs. Before presenting the data collected during these interviews it is important to detail the procurement context in which these data were collected.

Nolden and Sorrell [19] highlight the emergence of public sector frameworks as a key feature of the UK Energy Performance Contracting market in response to the relatively onerous requirements of EU procurement legislation. In a framework procurement, a single process, compliant with EU procurement rules is undertaken to select a pool of providers. Individual Clients can then select providers from the framework for their specific projects without the need for a full EU-compliant process. In RE:FIT this secondary selection process, carried individual projects, is termed a "mini-competition". Providers are appointed to the framework for a fixed period and the framework procurement is repeated at the end of each period. The RE:FIT framework is currently on its 3rd iteration [21].

Initially, a single process was available for Clients selecting their preferred ESCO through the RE:FIT framework: the target bid process. Under this process bidders carried out high-level assessments of energy saving potential at the sites included in the procurement. The preferred supplier was selected based on this information and subsequently carried out more detailed assessments of each site to develop Investment Grade Proposals (IGPs) which would be signed off by the client and form part of the contract documentation. Crucially, the energy savings within the more detailed IGPs were required to be at least as high as those predicted in the competitive bidding phase. If the energy savings in the IGPs were lower than those originally projected, the Client would have the right to reject the proposals and would have no liability for the costs the preferred supplier had incurred in developing them [129, schedule 2A, Clause 5.4]. Subsequently, a second process was developed as an alternative: the partner bid process. In this process bidders are not required to produce high level assessments of energy savings (although some examples may be required to enable a technical evaluation to be undertaken) and a partner is selected earlier in the procurement process. Only the preferred supplier will produce high level assessments of energy savings for each site and there is no fixed level of savings which must be delivered at the point at which the preferred supplier is selected. The two different processes are shown diagrammatically in figure 6.2.1.

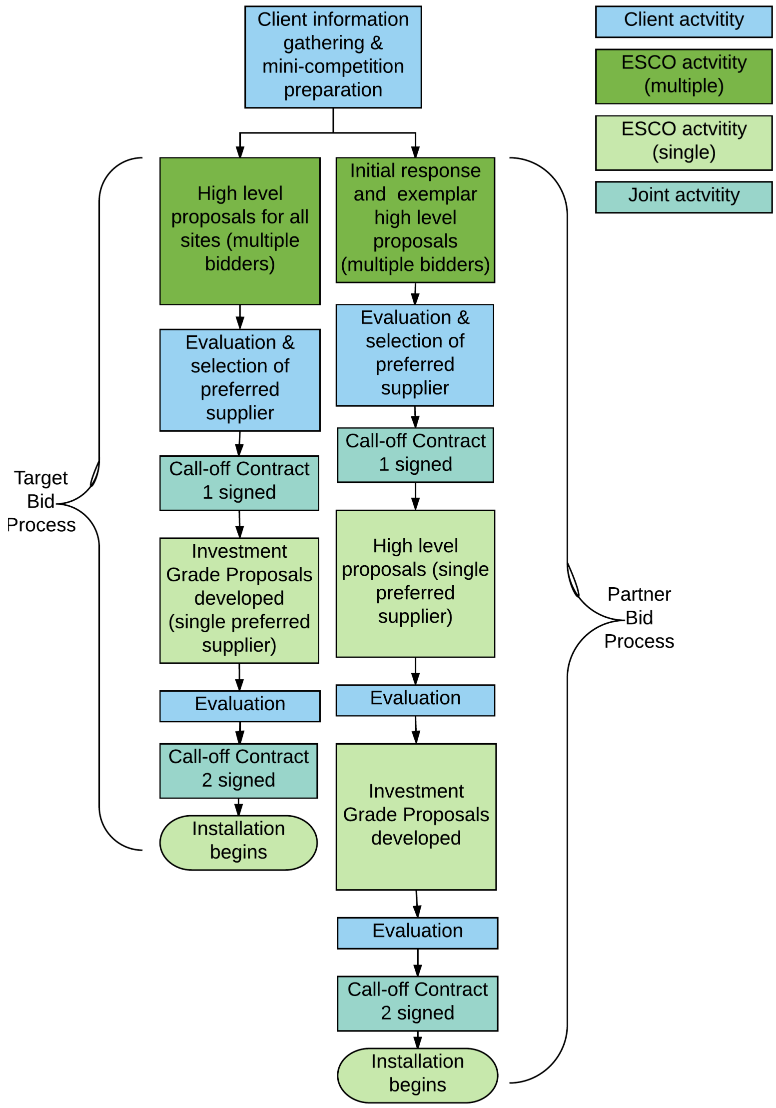


Figure 6.2.1: RE:FIT target and partner bid processes

These two different processes have important implications for transaction costs: firstly, since selection of the preferred supplier takes place later in the process in the target bid approach, transaction costs for unsuccessful bidders are higher than in the partner bid approach. However, for the successful ESCO, transaction costs would in principal be the same as the same amount of work is ultimately undertaken in each process. Secondly, although the client has lower bargaining and decision costs in the partner bid approach, only evaluating high level assessments from a single bidder, policing and enforcement costs are likely to be higher. This is because the guaranteed level of energy savings is developed in competition in the target bid approach but post-competition in the partner bid approach.

6.2.1 ESCO transaction costs

Section 4.6.2 sets out the process by which ESCOs were selected for inclusion in this study. The rationale for the data collection approach is detailed in section 4.6.3.1 and the interview schedule is contained in table 4.6.4. Interview materials can be found in appendix C.

Contact details were obtained for 14 of the 16 framework contractors through industry contacts, recruitment by the framework manager and personal approaches at industry events. Through this process, four potential participants ruled themselves out due to their lack of previous experience in the sector or a low-likelihood of participation in a schools project. The remaining 10 ESCOs all consented to participate in the research. However three of the interviewed ESCOs declined to provide transaction cost data. This resulted in an overall response rate of 58% which compares favourably with the response rates for a much larger study in the US conducted by Larsen et al. [52]. Relatively few responses were obtained from the construction/engineering/FM category so an additional participant was recruited who represented an organisation who had been involved in the previous RE:FIT framework but whose organisation had made a strategic decision not pursue inclusion on the current framework.

All interviews were recorded with the consent of the interviewees; recordings were annotated and coded using Nvivo [176]. However, since interviewees participated in the study under condition of anonymity, no transcripts are included in this thesis (a sample of annotated excerpts are included in appendix G). To avoid biasing responses from interviewees and potentially influencing the market in which all interviewees are currently direct competitors, interview data were not processed until all interviews had been completed. All interviewees provided numerical responses either in the form of minimum and maximum values for a particular category or a single value for each category. One organisation provided values for each cost category expressed as a proportion of estimated installation values for each project. However, the estimated installation values were significantly higher than those provided by the quantity surveyor. The initial data provided by this organisation were rejected as outliers and replaced with recalculated data using the quantity surveyor's estimated installation values as the base for calculation.

ESCOs were asked to provide four categories of cost information for each of the six projects:

- bidding costs: the costs which a potential supplier incurs to win a contract. Bidding costs include all the costs which are incurred at risk including any design and survey costs

- development costs: the costs which are incurred by a supplier after selection by the client. Development costs include finance, legal and administrative costs but exclude design costs

- project management costs: the costs of delivering the installation and operational phases

- gross margin: the excess of revenue from the contract divided by the costs of labour and materials required to perform the contract i.e. excluding overheads.

This breakdown was used to make it easier for interviewees to work through the costs in recognisable stages, so as to increase the likelihood of accurate responses. However, despite the descriptions provided, it is not possible to be certain that all costs provided represent exactly these categories. The three cost categories: bidding costs, project development costs and project management costs were expected to be strongly correlated, as a result of individual interviewees taking different approaches to the allocation of costs across the three phases. As a result, treating the three categories as independent inputs would understate the overall variation in ESCO transaction costs. Since the correlations are expected to differ across the respondents, the three cost categories were summed to create base data from which samples could be drawn, as described below. The resulting samples for total ESCO cost were then prorated for the length of each phase. This introduces a timing effect since costs may be being incurred earlier or later than would be the case in practice; however, since the overall development period is only seven months, this effect is expected to be negligible.

The small number of data points collected for transaction costs led to the need for a bootstrapping approach to create a probability distribution from which values could be selected. Anonymised raw data were reviewed with framework managers who are currently active in delivering projects using the RE:FIT framework. These reviews suggested that the upper and lower values for each category were extreme values which would be possible but not likely. Consequently a distribution which did not over-emphasise the extremes was preferred. A triangular distribution was selected since this could be constructed with the available data from minimum, maximum and median values. This approach was preferred to using a binomial distribution for which estimation of parameters would have been required.

Aggregated responses are shown in table 6.2.1; calculated values have been rounded to the nearest thousand pounds to reflect the precision with which ESCO responses were collected.

The resulting distributions for ESCO transaction costs are shown in figure 6.2.2. Two effects are apparent from figure 6.2.2; firstly that there is much less agreement about the transaction costs for the largest projects, and secondly, that the question order may have resulted in anchoring effects. Responses were sought to the projects in the same order in each interview (Project A to Project F). The resulting distributions suggest that responses to the second project in each scale pair (Projects A and B, Projects C and D, etc.) may have been driven by the response to the first.

Table 6.2.1: Aggregated ESCO transaction cost results

Project	Primaries	Secondaries	ECM set	Transaction costs			Margin		
				Min	Max	Median	Min	Max	Median
A	6	0	1	£29,000	£69,000	£39,000	6%	25%	11%
B	6	0	2	£34,000	£92,000	£49,000	5%	25%	12%
C	10	2	1	£62,000	£220,000	£116,000	6%	20%	14%
D	10	2	2	£72,000	£296,000	£143,000	6%	20%	13%
E	20	4	1	£92,283	£462,000	£232,000	5%	20%	11%
F	20	4	2	£151,000	£620,000	£253,000	5%	20%	13%

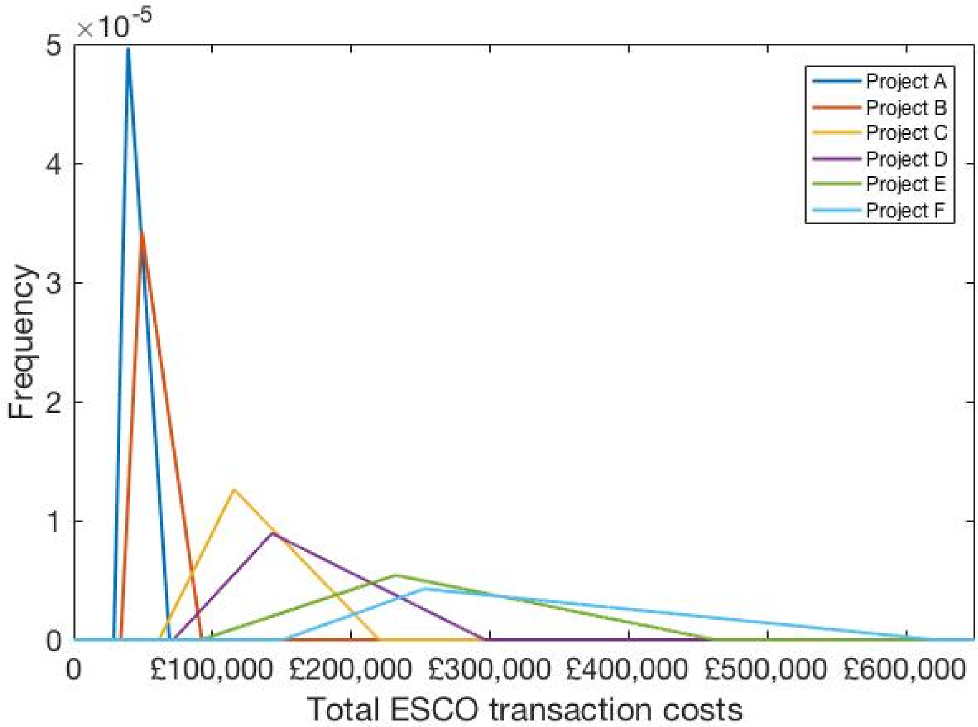


Figure 6.2.2: Distribution of ESCO transaction costs for each project

In contrast, the distribution of results for project margin shown in figure 6.2.3 suggest a broader spread for the two smallest projects (A and B) than for the other four projects. While the narrower spread of transaction costs might be indicative of a more competitive market for these projects, it seems more likely that experienced ESCOs limit their transaction costs to fit the budget they believe will be available for the project. The wider spread of margin suggests that these projects are less competitive; the number of interviewees indicating an interest in pursuing the projects provides some support for this (six for project A, 7 for B, C and D and eight for E and F).

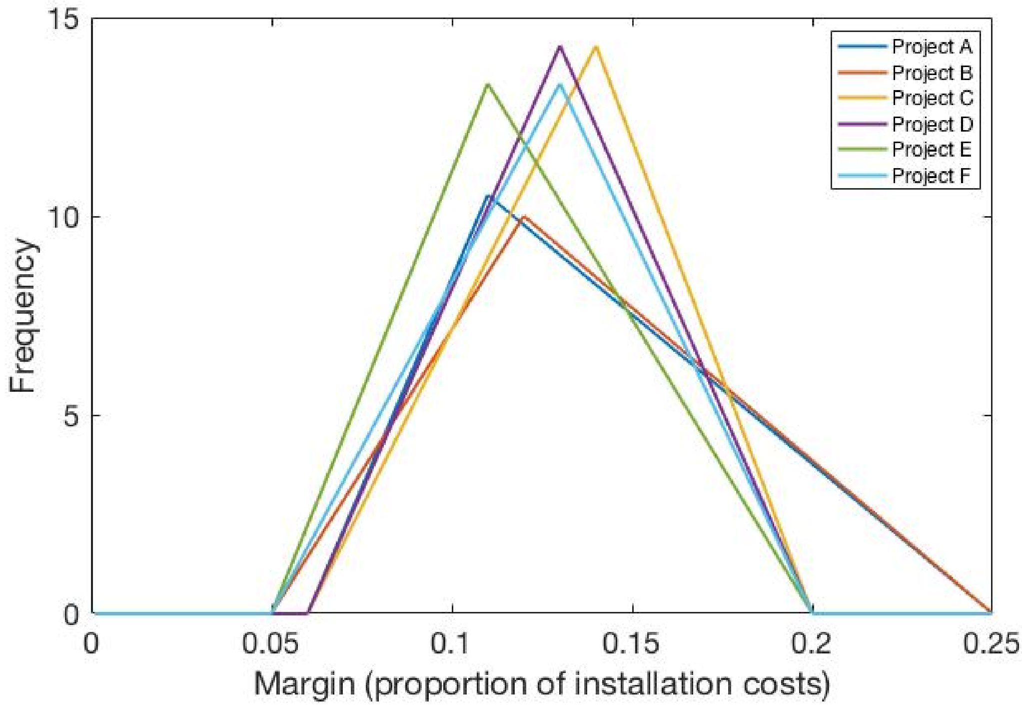


Figure 6.2.3: Distribution of ESCO margin requirements for each project

6.2.2 Client transaction costs

Section 4.6.3 explains how clients were selected for inclusion in the study. Details of the interview schedule can be found in table 4.6.3, client interview materials are contained in appendix D. Two key issues arose in collecting data for client transaction costs; the first related to the level of experience of clients, each of whom had only procured a single EPC project; this was in contrast with the level of experience of ESCOs, each of whom had submitted several bids. In addition, a number of ESCOs described detailed governance arrangements requiring the expected cost of a project to be calculated as part of an approval to bid process. The second issue in relation to obtaining data on client transaction costs is the overwhelming focus on external costs when considering the cost of public sector procurement. The literature relating to public sector procurement costs shows little evidence of consideration of internal costs, in particular staff time [177]. This was seen in an earlier study [2] where clients found it difficult to provide estimates for transaction costs. To avoid adding unnecessary uncertainty, clients were asked to provide details of the person-hours required for each stage of a project, as this reflected data in which they were expected to have more experience and confidence.

The four clients interviewed were at various stages in the process: two had completed procurement and installation phases of their projects and were well-established in the measurement and verification process while the other two had completed procurement phases but in one case the selected service provider had withdrawn from the market prior to installation of ECMs and in the second case, the project was approaching the installation phase. Figure 6.2.4 illustrates the level of experience of each client respondent and the type of procurement they had undertaken. The two respondents highlighted in red are those who provided estimates for the six case study projects, while the two shown in black provided details of their own transaction costs for similar projects.

Responses are summarised in table 6.2.2, shown as the actual figures quoted. The two responses for actual projects were allocated to a case study project based on number of sites. Apart from one respondent, who reported incurring external costs due to a lack of internal resources, all respondents had delivered their projects using only in-house resources. The external costs for respondent two were converted to a time-budget using an hourly rate, to allow like for like comparison.

The significant difference between the data provided by respondent one who had undertaken a target bid procurement process and the other respondents suggests that the choice of procurement route has a material effect on costs for the client. This suggestion is supported by the responses provided in the interviews where respondent four described a significant quality control and monitoring role for the client including a ‘clerk of works’ role and regular

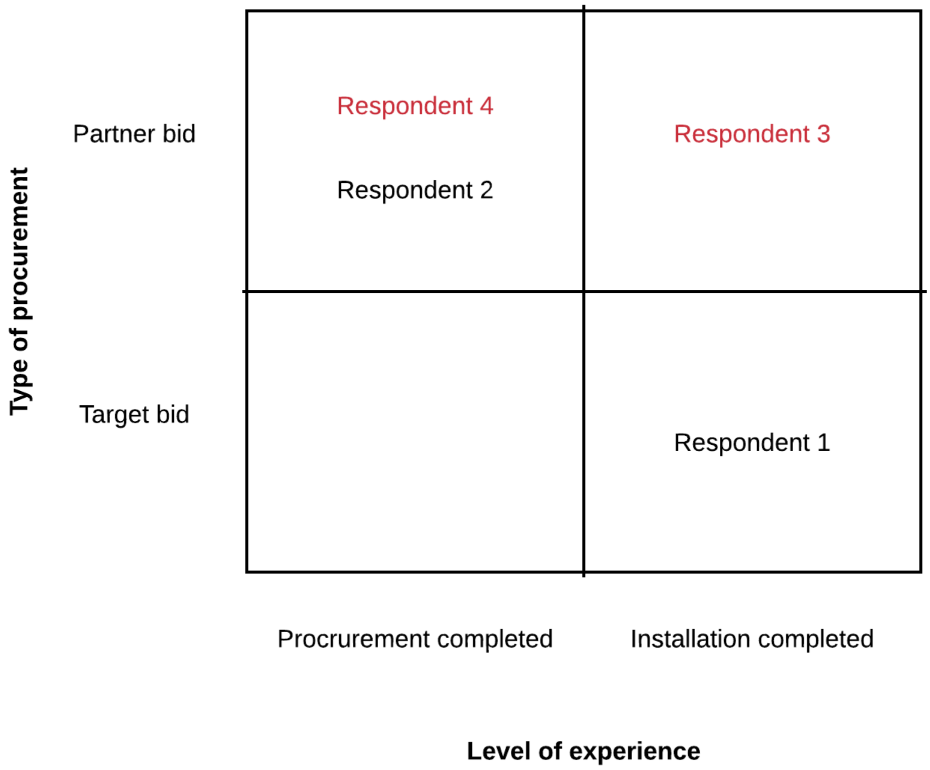


Figure 6.2.4: Level of experience and type of procurement undertaken

Table 6.2.2: Client person-hours required

Project	Total hours prior to installation				Annual hours from installation start			
	R1	R2	R3	R4	R1	R2	R3	R4
A			2793	2775			1125	750
B			2793	2775			1125	975
C	1092	2833	2793	2775	178		1125	1350
D	1092	2833	2793	2775	178		1125	1500
E			3119	2775			1125	1800
F			3119	2775			1125	1900

site inspections. The same level of detail was not available for respondent one; however, interview data for two target bid procurements collected during the pilot study showed a clear instruction from the framework managers to reduce levels of due diligence and instead rely on the guarantee. As a result, it seems clear that it is necessary to treat the two types of procurement separately and the decision was taken to exclude the data from the target bid project. The increased policing and enforcement costs in the partner bid are incurred in order to replace the controls imposed by bidders submitting prices in competition and it is assumed that the two processes are equally successful in controlling rent-seeking behaviour by the ESCOs. While confirming this assumption would require the collection of an additional data set and is considered to be beyond the scope of the current study, it is in-line with predictions from the transaction cost literature. In particular, Bajari and Tadelis [178] highlight that Fixed-Price contracts, where design work is largely complete prior to contract signature, create incentives for cost reduction on the part of the contractor. These are accompanied by the risk that quality may be compromised as a result. In Cost-Plus contracts, appointment of the contractor occurs at an earlier stage of design development and an agreed mechanism exists for the calculation of costs. Bajari and Tadelis note a preference for Cost-Plus contracts on more complex projects in which design is likely to be less fully developed due to a greater number of unknowns. However, the greater incentives for quality need to be balanced against the need for greater administration. Since the EPC projects considered in this study are straight-forward from a technical perspective and the buildings in which they are installed are also relatively simple, this suggests that the additional administrative burden of a cost-plus arrangement, exemplified by the partner-bid arrangement is likely to be unwarranted.

Although the responses did not reflect a variation in person-hours based on the scale of the project, this was at odds with the types of activities described in the interviews where there was a focus on information gathering and liaison with schools prior to commencement of the procurement process, these are activities which would scale with the number of sites. This disparity between the two types of data collected was addressed by increasing the range for the quantitative data to reflect the qualitative discussion of work involved. For the partner bid approach the median of the three responses was assumed to form the upper bound for smallest projects (A & B) with the lower bound assumed to be 20% lower and a uniform distribution was used to reflect the level of

Table 6.2.3: Partner bid adjusted hours

Project	Total hours prior to installation			Annual hours from installation start		
	Min	Max	Median	Min	Max	Median
Project A	2,227	2,784	2,506	750	1,125	938
Project B	2,227	2,784	2,506	750	1,125	938
Project C	2,775	2,833	2,793	1,125	1,350	1,238
Project D	2,775	2,833	2,793	1,125	1,350	1,238
Project E	2,775	3,119	2,947	1,125	1,800	1,463
Project F	2,775	3,119	2,947	1,125	1,800	1,463

uncertainty in this distribution. For the medium scale projects (C & D) the collected data were used to represent the minimum, maximum and median values of a triangular distribution. For the largest projects (E & F) the collected data were again used to represent the minimum, maximum and median values of a triangular distribution as shown in figure 6.2.3.

These time-budgets were converted to costs by applying an hourly rate calculated based on a 37 hour working week with 27 days holiday and 8 national bank holidays [179] using the method set out in Messenger et al. [180]. The annual salary range was taken from Inner London Borough pay scales [181]. The starting point salary was taken as point 37 and the upper salary limit was taken as point 46. These were based on advertisements in May 2017 on a specialist local government jobs website [182] for a Sustainability and Regeneration Officer and for a Team Leader - Business Development & Environmental Efficiency. The total cost of employment was calculated by adding employer's national insurance contributions and pension contributions to the Local Government Pension Scheme based on the University of Bath employee "on cost" calculator[183]. Calculated costs are shown rounded to the nearest thousand pounds in line with the approach taken for ESCO transaction costs.

Table 6.2.4: Partner bid client transaction costs

Project	Total hours prior to installation			Annual hours from installation start		
	Min	Max	Median	Min	Max	Median
Project A	£53,000	£83,000	£67,000	£18,000	£34,000	£25,000
Project B	£53,000	£83,000	£67,000	£18,000	£34,000	£25,000
Project C	£67,000	£84,000	£75,000	£27,000	£40,000	£33,000
Project D	£67,000	£84,000	£75,000	£27,000	£40,000	£33,000
Project E	£67,000	£93,000	£79,000	£27,000	£54,000	£39,000
Project F	£67,000	£93,000	£79,000	£27,000	£54,000	£39,000

6.2.3 Defining the client organisation

Thus far in this study the "Client" has been treated as a homogeneous entity; however, the school system in England and Wales has a "quasi-market" organisation [184], comprising a range of different types of schools each with differing governance arrangements. As illustrated in figure 6.2.5, central state funding is allocated to either Local Government or to an Academy Trust. Academy Trusts may be responsible for one or more schools (known as a Multi-Academy Trusts or MATs).

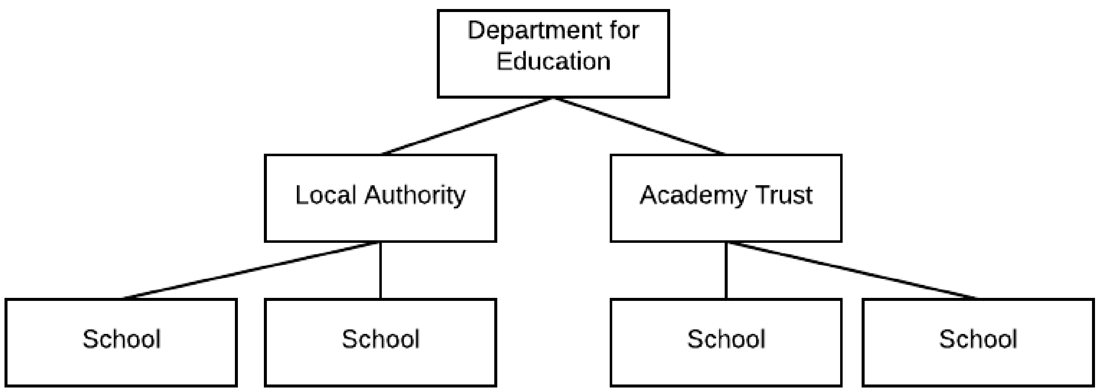


Figure 6.2.5: Structure of funding arrangements for schools in England and Wales

The MAT model presents a homogeneous organisational structure, since a key driver for the establishment of MATs is the streamlining of financial responsibilities [185]. In contrast, while a local authority may be responsible for a large number of schools in a local area, most funding is delegated to the individual schools, with responsibility for allocation of funding resting with each school's governing body [185]. As a result, for local authority controlled schools, while the initial Client is the local authority who enters into the framework agreement with the ESCO, individual schools would enter into the installation agreements with the ESCO. The performance guarantee is contained within the framework agreement, meaning that payment for any shortfalls would be made to the local authority and then passed to the schools. Since the Education Act (2002)[186] prohibits local authority controlled schools from borrowing money, additional finance above the interest-free funding available through the government backed Salix programme [187] must be procured by the local authority. Individual schools are generally responsible for payment of their own utility bills but generally use a buying consortium which means that all schools in the consortium would pay the same rates. Figure 6.2.6 illustrates the different responsibilities of different constituent parts of the client. A result of this lack of homogeneity is that different risks are borne by different parts of the client and a single client outcome has the potential to mask effects at an individual level. This is particularly the case for any energy performance risk not covered by the performance guarantee, since this would be borne by the individual school. Some of this risk might eventually be borne by the local authority if it cannot be absorbed within the school budget [188].

6.3 The impact of transaction costs on returns

The framing of decisions about energy performance contracting as a choice between continuation of existing arrangements ("in-house"), or installation of retrofit measures as part of an energy service ("outsourced") set out in Chapter 3 leads to a broader definition of transaction costs than the data collection,

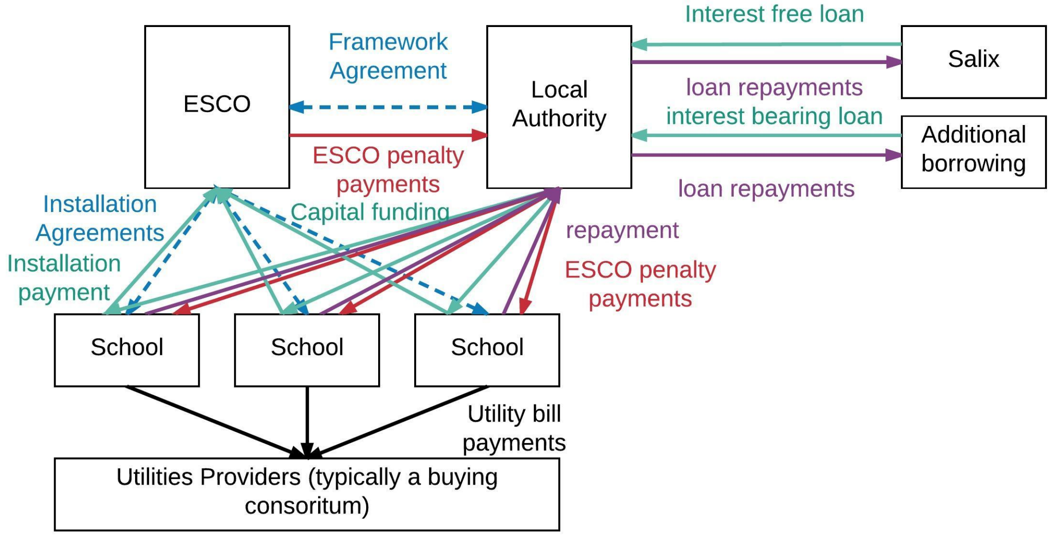


Figure 6.2.6: Local Authority contracting arrangements

bidding and negotiation costs detailed in sections 6.2.1 and 6.2.2. In this framing, in-house transaction costs are assumed to be zero since the existing arrangements involve only the payment of utility bills, administrative costs of which are assumed to be negligible. Transaction costs for the out-sourced option consist of the total payment to the contractor plus the client's internal costs.

The radial elementary effects approach to sensitivity analysis described in section 5.4 was applied to the stochastic DSCF model to explore the relative effects of the different input parameters to the DSCF model on returns for clients and contractors. In this setting, the elementary effects estimator of equation 5.1 is replaced by Jansen's estimator for total effects [189]:

$$ST_i = \frac{1}{2N}\sum_{j=1}^{N}(f(A)_j - f(A_B^{(i)})_j)^2 \qquad (6.1)$$

where:

N is the total number of estimates per parameter

$f(A)_j$ is the model output for the j^{th} input vector

$f(A_B^{(i)})_j$ is the model output for the j^{th} input vector which only the i^{th} parameter differs from $(A)_j$

Figures 6.3.1 and 6.3.2 show the sensitivity of client and ESCO returns to transaction costs and other project inputs for each of the 6 projects. Blue and green shading is used for transaction cost parameters and yellow tones are used for production cost related parameters.

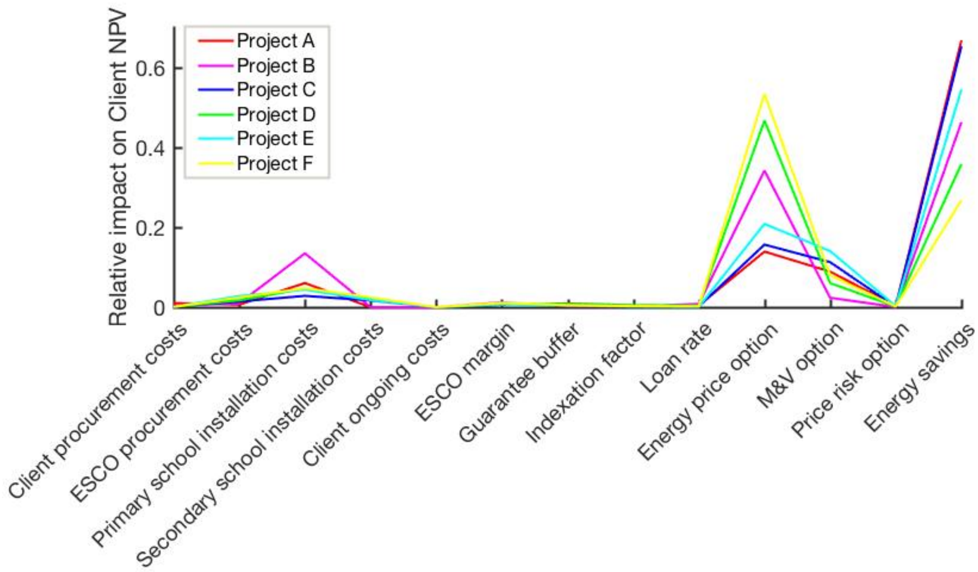


Figure 6.3.1: Sensitivity of client financial returns to input parameters

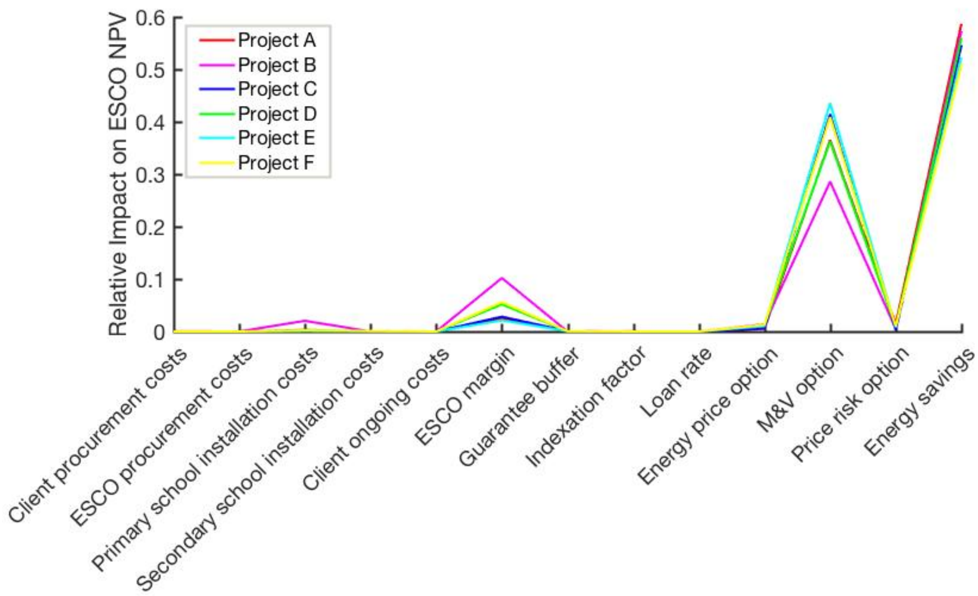


Figure 6.3.2: Sensitivity of ESCO financial returns to input parameters

The results shown in figures 6.3.1 and 6.3.2 indicate that although transaction costs are influential (particularly installation costs in the case of the Client and ESCO margin in the case of the ESCO) it is the overall level of energy savings that has the greatest impact on returns for both ESCO and Client.

6.4 Competitiveness of projects in practice

A request was made under the Freedom of Information Act 2000 [190] for details of projects procured between 2012 and 2017 using the RE:FIT framework:

- date of mini-competition launch
- date of selection of preferred supplier
- date of contract signature
- format of competition (target or partner bid)
- capital investment
- annual carbon savings
- annual electricity savings (kWh)
- annual gas savings (kWh)

Anonymised data for 34 projects were received in response. Data for annual electricity and gas savings were not available. Combined energy saving data were provided instead. Following discussions with the data provider, the number of bidders for each project was also included in the data set. While the data set is not sufficiently large to allow rigorous statistical analysis, an exploratory analysis was undertaken which affords an insight into the data.

Figure 6.4.1 suggests that there is no strong relationship between the number of bidders for a project and the overall capital investment.

Although data for transaction costs on the individual projects were not available, data were available on the bid format. As discussed in section 6.2,

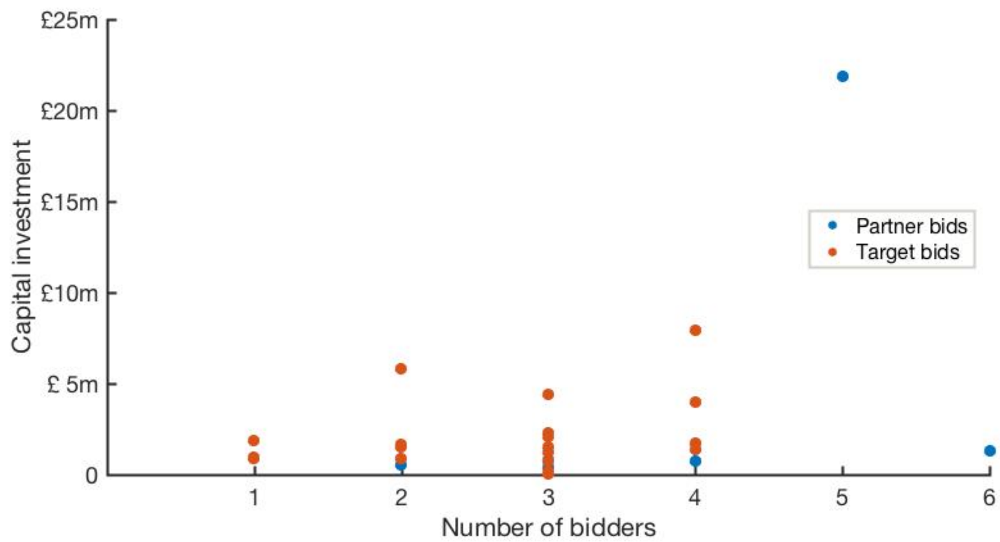


Figure 6.4.1: Capital investment and number of bidders

while transaction costs for the successful bidder would be the same under both models, the costs for the unsuccessful bidders are potentially quite different, with the partner bid approach requiring less information to be provided during the competitive process. Figure 6.4.2 shows a clear tendency for higher numbers of bidders for partner bid projects than target bid projects, even though the data in figure 6.4.1 suggests partner bid projects typically have lower capital investment values. Since lower capital value is likely to indicate lower technical complexity, this suggests that the selection of the procurement route is based on a desire to increase numbers of bidders for projects rather than on the need for a mechanism which allows greater design development post selection. The additional administrative burden such a mechanism requires [178] is not reported in project data.

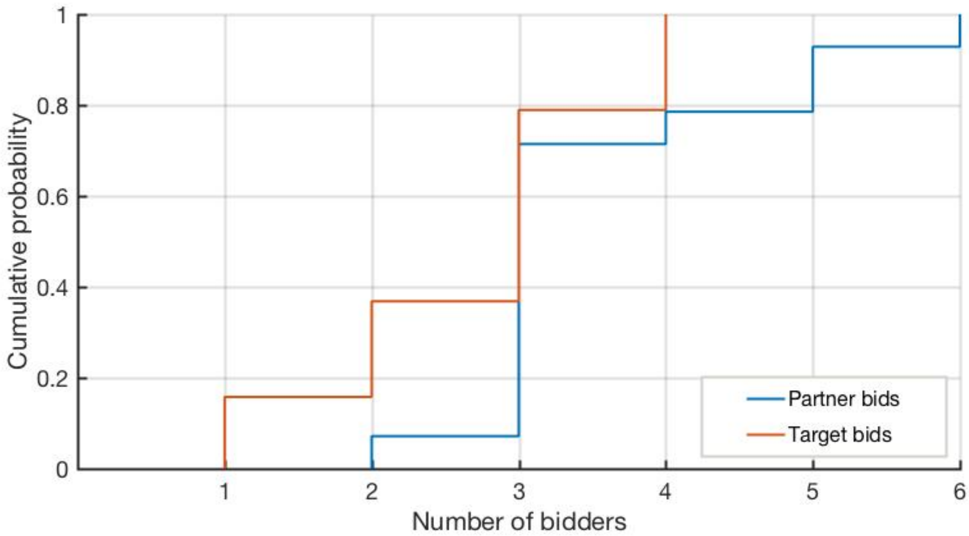


Figure 6.4.2: Cumulative distribution of bidders for partner and target bids

6.5 Support for hypothesis one

Sorrell [22] hypothesised that "Energy service contracting is more (less) likely to be used in situations where ...the market for energy service contracts is more (less) competitive" as a result of lower transaction costs in a competitive market. Since lower transaction costs mean lower costs overall it is clear that in a like for like comparison, projects with lower transaction costs are more likely to be successful. However, data obtained from the Client interviews and the Freedom of Information data suggest a more complex picture in which reduced transaction costs for the bidding ESCOs are achieved at the expense of increased Client transaction costs. This is because it is not overall transaction costs that are a determinant of competitiveness but rather the level of transaction costs at risk for unsuccessful bidders. Reducing the level of information required as part of the competition results in lower transaction costs for unsuccessful bidders and thus increases competition. However, while bidders may find reduced requirements for detailed information attractive, there is an important trade-off for clients who incur greater policing and enforcement costs to ensure that out-turn production costs are appropriate. Since data on Clients' in-house transaction costs are very limited, this effect is potentially unmeasured.

Chapter 7

The Impact of Measurement Choices in Determining Savings

7.1 Overview

The second research hypothesis set out in chapter 3 relates the success of an EPC project to the ease of measuring energy savings. A well defined framework exists for energy performance contracting projects, the International Performance Measurement and Verification Protocol (IPMVP) [79] which sets out different options for measuring energy savings. Sorrell [23] postulated, as set out in hypothesis two, that the easier (cheaper) measurement and verification (M&V) of energy savings is, the more suitable a project is for an energy performance contract. This chapter explores the impact of M&V approaches on project outcomes by considering the different approaches offered under IPMVP and the likely costs associated with each option. The different risk exposures under each option are discussed and the implications of the different M&V strategies are modelled for two different sets of energy conservation measures and a global sensitivity analysis is undertaken to determine the impact of the choice of strategy on financial returns for clients and contractors.

7.2 Approach to measuring savings

Wang et al. [63] note that measuring savings is a more nuanced process than is often assumed and identify four types of savings: predicted, guaranteed, measured and actual. The distinctions are important, particularly for the final two categories which are often conflated. As can be seen from table 7.2.1, the different IPMVP measurement options involve different measurements which would result in different values.

Table 7.2.1: Actual vs measured savings for each M&V option

M&V Option	**Description** [66]	**Actual vs Measured**	**Initial cost** [78]	**Ongoing cost** [78]
A	• Savings calculated separately for each measure • measurements taken for some variables • deemed (assumed) values used for other variables	• effects on other building systems are not included • accuracy depends on influence of deemed variables and accuracy of deemed value • only change in measured variable is included	0.5 - 3 %	0.1 - 0.5%
B	• savings calculated separately for each item • take measurements of all variables	• effects on other building systems are not included • measurements may encompass other effects eg. changes in patterns of use as well as changes due to ECM	2 - 8%	0.5 - 3%
C	• determine savings using utility bills	• measurements may encompass other effects eg. changes in patterns of use as well as changes due to ECM	0.5 - 3%	0.5 - 3%
D	• determine savings using a calibrated computer model	• accuracy depends on model assumptions • highly indeterminate models will have many plausible calibrated settings and impact of ECM may depend on which is selected [159]	2 - 8%	0.5 - 3%

Shonder and Avina [66] note that while using Option C allowed ESCOs to present savings in the way that made most sense to their clients it also exposed the ESCO to the risk of changes in the client's patterns of consumption over time. As a result, they report ESCO preferences shifting towards option A and

D approaches to mitigate this risk. Shonder and Avina raise the concern that in trying to reduce their risk, ESCO have “reduced the quality and appeal of ... performance contracting.” Stetz et al. [191] expressed a similar concern “Since the purpose of M&V is to provide assurance that project savings exist,. improper and excessive reliance on stipulations may effectively nullify savings guarantees."

7.3 ESCO approaches to M&V

As part of the interview process described in section 6.2 ESCOs were asked about their preferred M&V approach. In total 11 ESCO interviews were undertaken, 2 ESCOs declined to provide cost data and provided only general statements in relation to their preferred approaches to measurement and verification of savings for the case study projects. Appendix G contains transcribed excerpts of the parts of each interview which were coded at the M&V node.

All ESCO interviewees indicated that choice of M&V strategy would be dictated by the range of ECMs installed rather than by the number of sites. However, two ESCOs also highlighted client requirements as a deciding factor. This was accompanied by concerns that client monitoring requirements might entail additional cost which would reduce the available budget for interventions. The level of existing metering was also identified as a contributing factor in decisions about M&V methodologies.

Although ESCO responses agree with Shonder and Avina’s [66] contention that option A is preferred, only 4 of the interviewees explicitly addressed the risk of exposure to changes in client patterns of use as a driver for this position. Respondents were more likely to frame the choice of M&V strategy as a decision about a balance between cost of monitoring and level of detail, suggesting a decision between options A and B since, as indicated in table 7.2.1, costs would be expected to be similar for options A and C. Figure 7.3.1 shows the response for each item. In discussing the ECM groupings presented ESCOs identified that decisions about M&V would be based on the category of ECM and categorised each ECM as either lighting or heating related. For consistency these categories are used in figure 7.3.1.

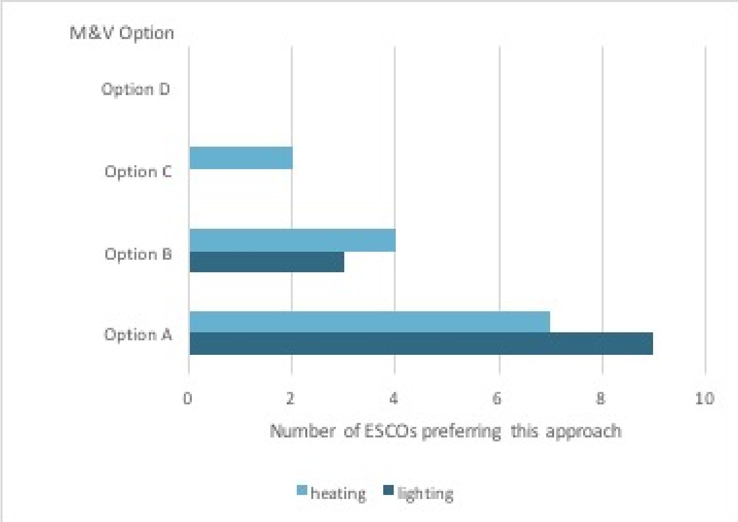


Figure 7.3.1: ESCO preferences for M&V approaches

Option D is primarily used for new construction where no baseline information is available and back-casting is required to create a notional baseline building without the relevant energy conservation measures in order that the impact of the measures can be assessed. Since the current study concerns retrofit of existing buildings rather than new construction it was anticipated that this option would be unlikely to be selected by ESCOs. This was borne out by the interview responses in which no respondents identified option D as a proposed approach.

IPMVP [79] defines interactive effects as "Any energy effects occurring beyond the notional measurement boundary" and advises parties "[f]ind a way to estimate the magnitude of these interactive effects in order to determine savings. Alternatively they may be ignored as long as the M&V Plan includes discussion of each effect and its likely magnitude." Interviewees were asked how they would deal with interactive effects if using an option A or B approach. Three of the responses could not be clearly coded, three interviewees indicated that interactive effects would be explicitly calculated and three stated that they would not be addressed.

7.4 Measured savings for different M&V options

The impact of different measurement boundaries was tested for the two archetype buildings by using the reduced-parameter energy model described in section 5.2.3 to model the energy consumption before and after retrofit. Variable parameters were kept constant between the pre and post retrofit models unless they were affected by the set of ECMs applied, resulting in pairs of pre and post retrofit models. This approach means that the distribution of energy savings that result is due to the uncertainties in patterns of use underlying the baseline energy consumption and not due to changes in patterns of use between the pre and post retrofit models. Details of the ECMs included in each set can be found in section 5.2.2. Changes in patterns of behaviour due to ECM installation were incorporated where the nature of the ECM made this inevitable, for example, changes to lighting and heating schedules following installation of new controls.

7.4.1 Electricity savings

Electricity savings were calculated in three ways, as set out in table 5.2.2. The resulting energy savings, given by the difference between a pair of pre and post retrofit runs are shown in figure 7.4.1 for the first set of ECMs, plotted against the baseline lighting hours. In the naturally ventilated primary school archetype, the lighting energy saving and the whole facility electricity saving are almost identical (in figure 7.4.1 this means primary school lighting energy maps directly on to, and covers primary school whole facility lighting energy). Reducing lighting energy affects the heating system which must compensate for reduced waste heat in the building, the resulting increase in electrical power consumption for pumps etc in the heating system accounts for the small difference between the two figures. A correlation between baseline lighting hours and energy savings can be seen ($R^2 = 0.33$).

The secondary school archetype is partially mechanically ventilated, meaning that in addition to the impact on the heating system which is called on to replace waste heat during the heating periods, there is a synergistic impact on the cooling systems as the need to off-set waste heat during cooling periods is significantly reduced. This results in higher savings measured at the whole facility level than at the lighting circuit level. As a result the correlation between baseline lighting hours and lighting energy savings is higher ($R^2 = 0.65$) than that for the whole facility electricity savings ($R^2 = 0.50$).

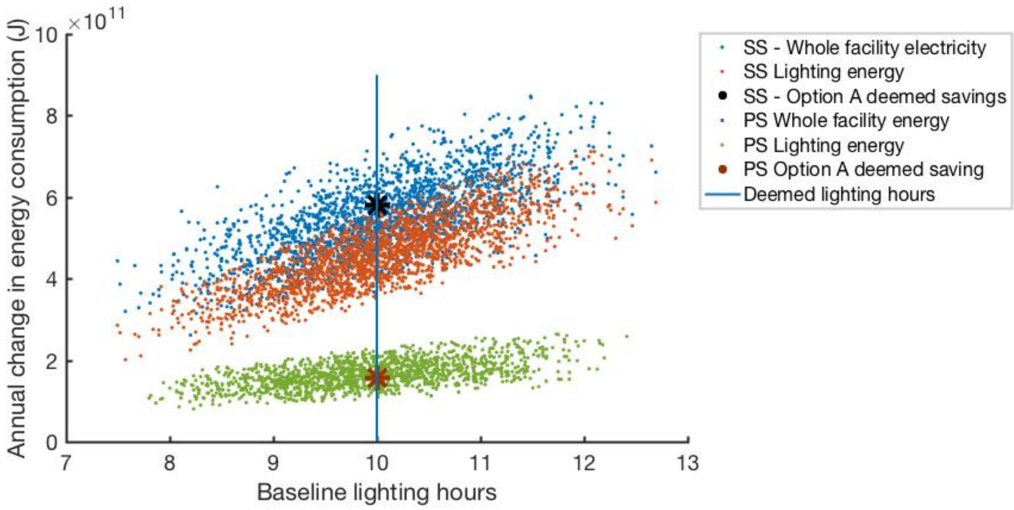


Figure 7.4.1: Primary and Secondary school electricity savings - ECM set 1

Similar results can be observed for the second set of ECMs in figure 7.4.2 with $R^2 = 0.37$ for the primary school and $R^2 = 0.51$ and $R^2 = 0.61$ for secondary school whole facility electricity consumption and lighting energy respectively.

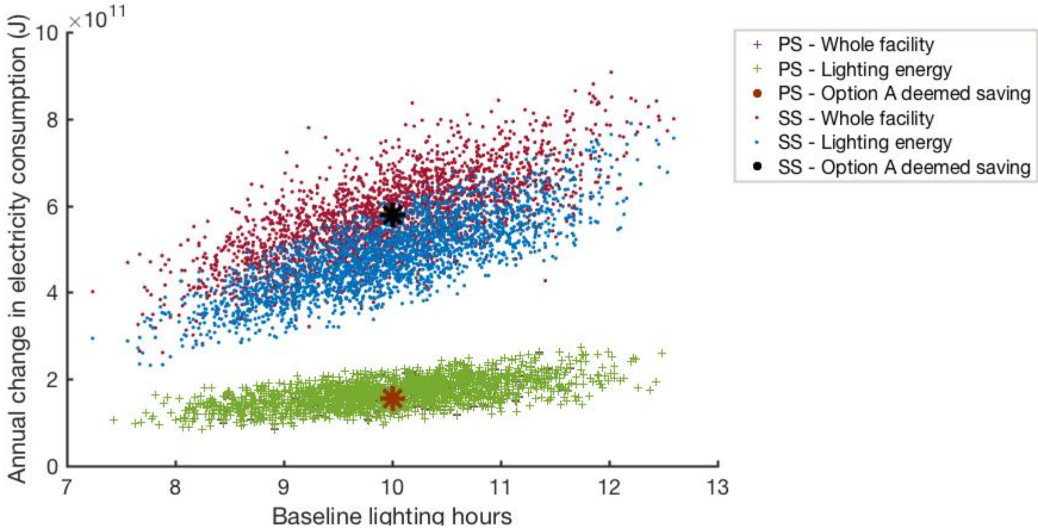
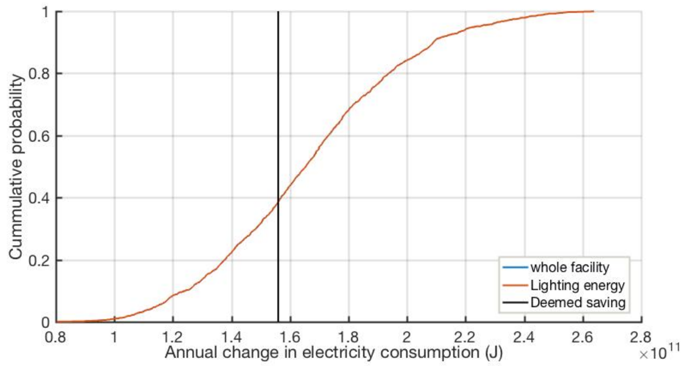
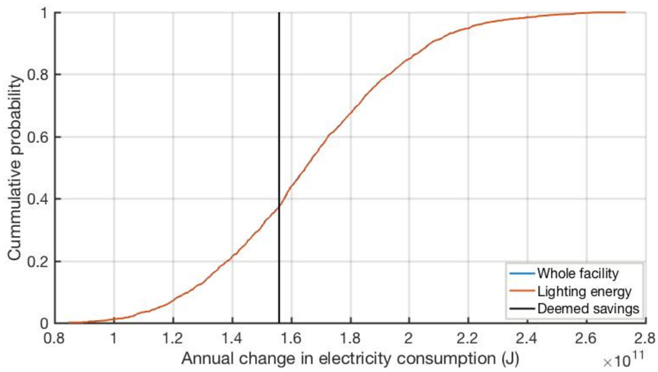


Figure 7.4.2: Primary and Secondary school electricity savings - ECM set 2

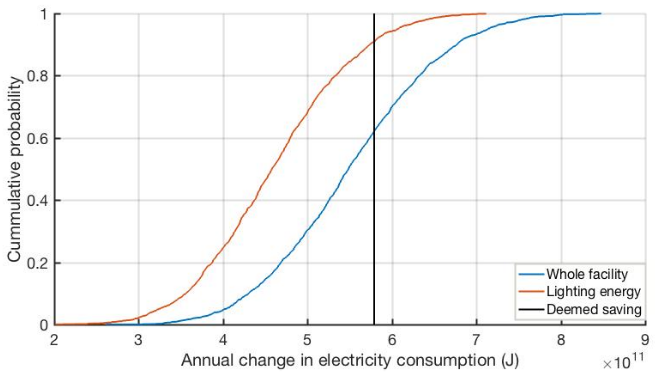
Plotting the cumulative distribution of electricity savings for the two archetypes under the same two sets of ECMs as shown in figure 7.4.3 illustrates the near-perfect agreement between lighting energy and whole building electricity savings for the primary school. There is a systematic difference between the two measurements in the secondary school model due to the existing of cooling equipment in some areas which experiences a synergistic reduction in consumption when waste heat in the building is reduced. The contrast between the single deterministic value and the broad spread of values derived from the whole building or lighting energy outputs is stark.



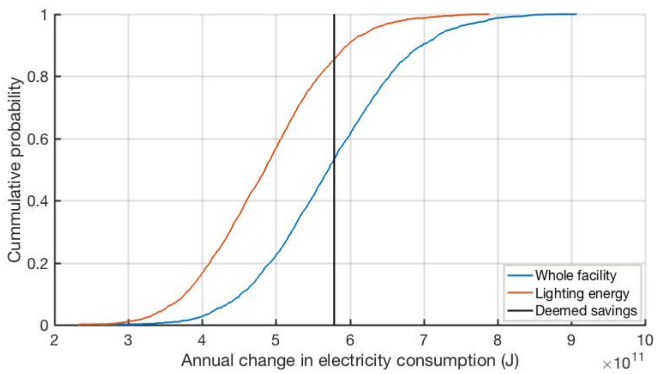
(a) Primary school - ECM set 1



(b) Primary school - ECM set 2



(c) Secondary school - ECM set 1



(d) Secondary school - ECM set 2

Figure 7.4.3: Cumulative distributions of electricity savings

7.4.2 Gas savings

The calculation approach for electricity savings was applied to calculating gas savings. However, in contrast with measuring electricity savings, the measurement of gas savings associated with a particular ECM is significantly more challenging due to the interactions of a wide range of heat loss mechanisms. For some ECMs, no measurement is thought to be possible and a purely deemed approach was suggested under option A. For the purposes of comparison, a option B approach was investigated by installing heat meters to measure boiler output. Although heat meters are commonly used in biomass fuel heating systems they are not commonly used in other types of heating system.

The distributions of gas savings for the first ECM set are shown in figure 7.4.4, since the ECMs installed do not affect the hours of heating, these are held constant in all the model evaluations. Gas savings are plotted against baseline lighting hours instead.

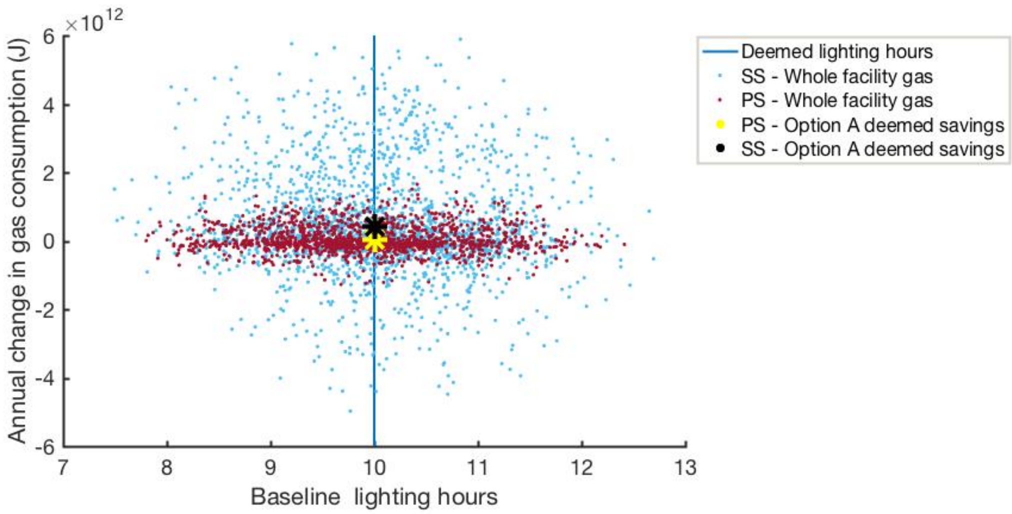


Figure 7.4.4: Primary and Secondary school electricity savings - ECM set 1

In order to derive the input energy savings from the metered heat output used to test option B in the second set of ECMs it is necessary to adjust the output to take account of the boiler efficiency. This is done using the assumed boiler efficiency pre and post retrofit. Although these figures are both imprecise, they would not result in the systematic gap between whole facility gas consumption and the heat meter output shown in figure 7.4.5, instead this gap is due to the overestimation of boiler efficiency which results if the actual part load operating profile is not taken into account. In order to correct for this it would be necessary to measure the part-load ratio of each boiler at each time-step. Since the heating hours are affected by the ECMs in the second set they are treated as a variable parameter and gas consumption is shown plotted against baseline heating hours in figure 7.4.5.

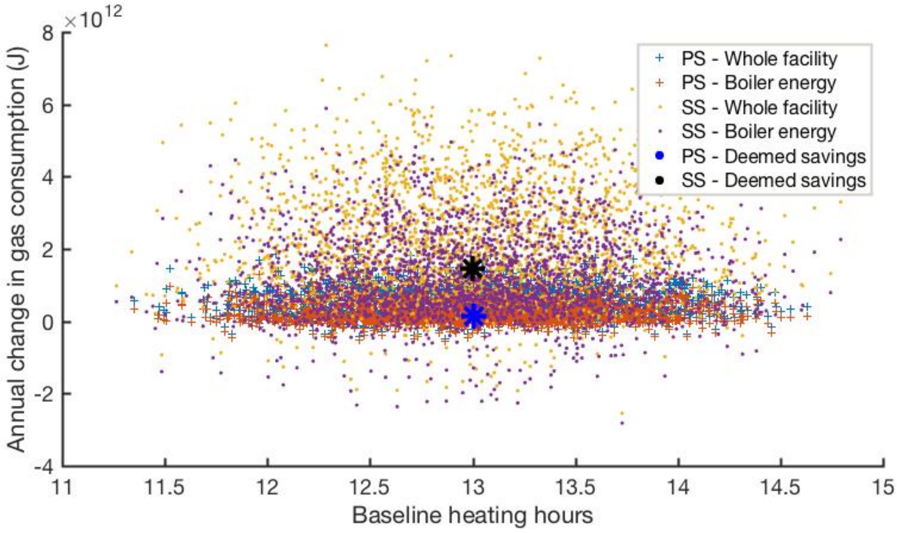
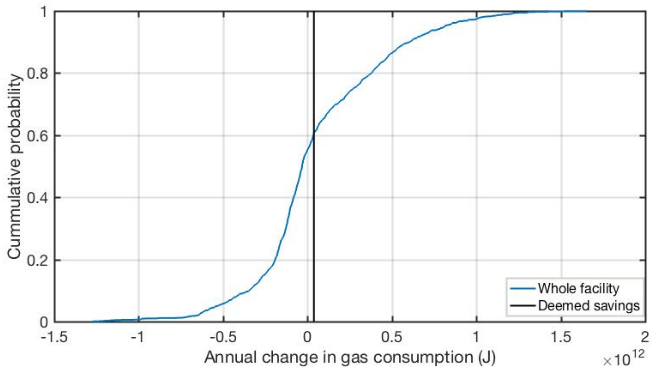
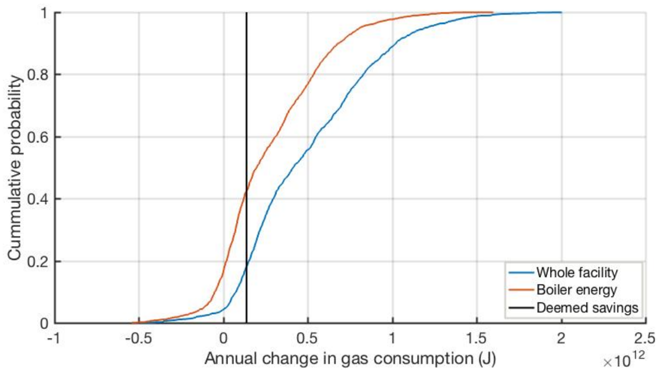


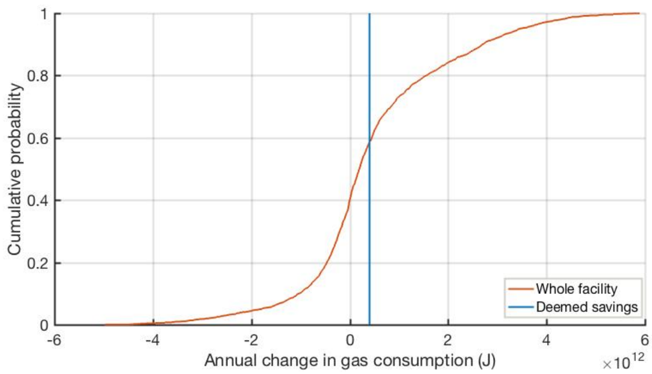
Figure 7.4.5: Primary and Secondary school gas savings - ECM set 2



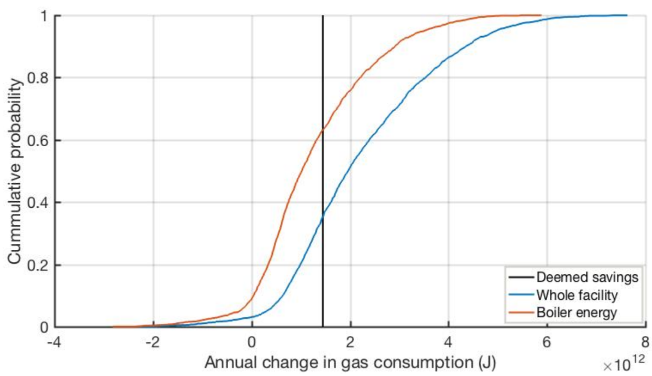
(a) Primary school - ECM set 1



(b) Primary school - ECM set 2



(c) Secondary school - ECM set 1



(d) Secondary school - ECM set 2

Figure 7.4.6: Cumulative distributions of gas savings

Table 7.4.1 shows the savings which result using each measurement option for the two building archetypes and sets of ECMs. It can be seen in all cases that there is relatively close agreement between the mean savings calculated using options B & C and the option A deemed value for electricity savings. The standard deviations are small compared with the mean values suggesting that the choice of M&V option may not make a significant difference to outcomes. In contrast, gas savings are significantly more volatile, particularly for the first ECM set, which includes only one intended measure, heating controls, but is also affected by the interaction with the lighting upgrade measure. Savings for the second ECM set are still much more volatile than electricity savings but the larger set of measures results in a portfolio effect with a smaller distribution of savings than the first set.

In each of the cases presented in table 7.4.1, the value of savings "measured" using IPMVP option A is identical to the level of predicted savings. This is because the measurement is limited to a test of the "potential to perform" [191], in other words, the test is met if the correctly specified ECM is installed, but its performance in operation is not measured. While it can be argued that the measured savings for option B and C are slightly higher for electricity than the option A savings and thus that option A represents a reasonable approximation of the mean, the more important issue is that under this approach the performance of the ECM is not actually guaranteed, only its specification. This is significant since similar protection is likely to exist under the terms of an underlying installation contract and the additional contractual layer that the performance guarantee represents is likely to increase costs in two ways: firstly, directly by increasing negotiating costs. Secondly, this procurement model effectively restricts the market of available suppliers to those with sufficient covenant strength to provide a performance guarantee, even if there are, in practice, no additional risks under the guarantee.

In the preceding discussion, the whole facility change in energy consumption has been treated as synonymous with the actual savings as a result of the

Table 7.4.1: Savings values for each M&V option

Case		Predicted savings	Mean measured savings (std. dev)		
			Option A	Option B	Option C
Primary school	ECM1 Electricity	42.46%	42.46%	44.96% (5.16%)	45.15% (4.96%)
	ECM1 Gas	8.6%	8.6%	n/a	4.23% (39.91%)
	ECM2 Electricity	42.38%	42.38%	44.90% (5.10%)	44.88% (5.10%)
	ECM2 Gas	28.82%	28.82%	17.97% (23.83%)	38.04% (23.88%)
Secondary school	ECM1 Electricity	37.72%	37.72%	29.87% (4.15%)	35.76% (4.23%)
	ECM1 Gas	8.70%	8.70%	n/a	3.76% (31.52%)
	ECM2 Electricity	37.85%	37.85%	31.62% (4.17%)	37.33% (4.31%)
	ECM2 Gas	27.79%	27.79%	20.30% (19.61%)	39.13% (19.87%)

installation of the ECMs. In practice, as highlighted by Shonder and Avina [66] the change in whole facility energy consumption will encompass a range of factors which are unrelated to the installed ECMs. Wang et al. [192] demonstrated that while variations in weather resulted in changes of between 4 and 6% in energy consumption in a commercial office building in a range of US cities, the variation in energy consumption due to occupancy patterns and behaviours was much greater, with poor practice exemplars consuming more than double that of best practice modes of operation.

The sensitivity analysis of the energy models reported in section 5.4.3 was revisited to consider how much influence different categories of building parameter have on the building energy consumption. In contrast with the analysis of section 5.4.3, where the aim was to identify the most influential parameters, the aim here is to calculate the proportion of uncertainty due to different categories of input. The input parameters were assigned to 8 categories (equipment, fabric, geometry, occupancy, operation, systems, weather, model) and Jansen's estimator for ST_i calculated for each category as described in section 6.1. The resulting category sensitivities are shown in figure 7.4.7 which illustrates the categories of input which make the largest contributions to uncertainty in the electricity and gas consumption of the primary and secondary schools respectively. Operational parameters eg. boiler hours of operation and lighting hours are the most influential category for all outputs except electricity consumption in the primary school where they are the second most important category after building systems. These results are consistent with those from Wang et al. [192]. A consequence of this is that use of an Option C M&V approach exposes the ESCO to significant fluctuations in energy consumption caused by changing patterns of use. Where these patterns are within the ESCO's control and can be monitored (e.g. installation of occupancy sensing to control lighting operation, or introduction of a Building Management System) this may be appropriate risk transfer if adequate monitoring data is available pre-intervention to identify usage patterns. Where usage patterns pre-intervention are uncertain, this risk remains significant. This result mirrors those of Ginestet and Marchio [81] who note that "planned orders have to be respected in order to make [option A] usable."

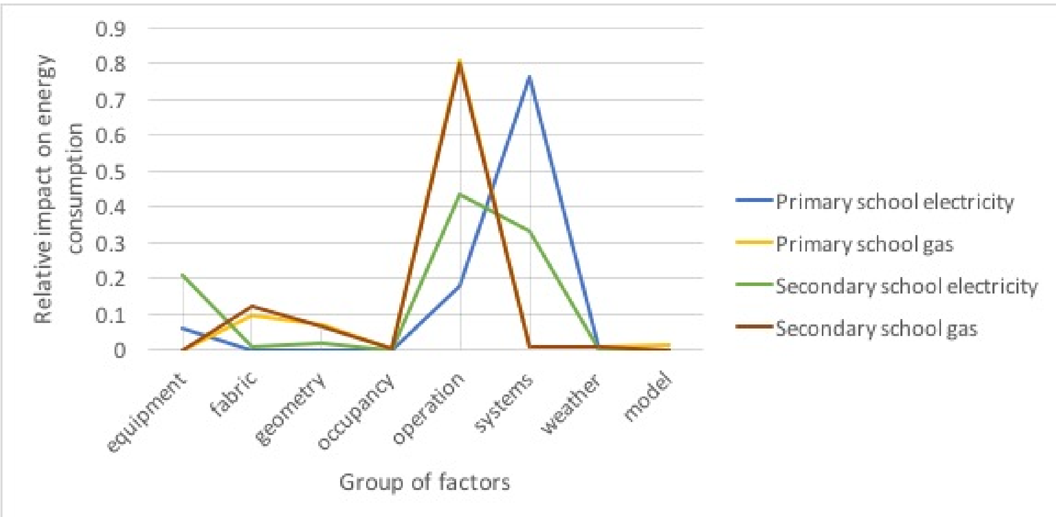


Figure 7.4.7: Sensitivity of energy models to different categories of inputs

Shonder and Avina's [66] characterisation of Option C as exposing the ESCO to the risk of change patterns of use reflects a broader simplification of IPMVP [79] commonly used within the industry, implying that option C is based on whole facility energy meters alone. As Kumar et al. [193] highlight, "estimated versus actual energy savings information will only be useful if the actual energy savings numbers are verified based on the measurement of those performance and operational parameters that are highly variable in nature." Despite the view of some ESCOs expressed in interviews that an IPMVP option B approach would offer protection, the same qualification is true of most retrofit isolation measures as well. In the examples modelled here, the isolation of the particular ECM (for example, lighting circuit) made no difference to the exposure of the ESCO to the risk of changes in patterns of use and occupation, the close match between the cumulative distributions for the two different sets of savings shown in figure 7.4.3 is a demonstration of this.

7.5 Sensitivity of project outcomes to M&V option choice

The sensitivity analysis runs presented in section 6.3 allow the contribution of the input parameters variance to the output variance to be considered. M&V option was treated as a discrete variable and samples generated using Sobol' sequences as detailed in section 5.4.2, samples were transformed to the input space by banding ($0 \leq x < 0.33, 0.33 \leq x < 0.66, 0.66 \leq x \leq 1$). The impact of M&V choice can then be evaluated across the full input space. Figure 6.3.2 (reproduced here as figure 7.5.1 for ease of reference) shows that the choice of M&V option is second only to the level of energy savings in significance for the ESCO. Figure 6.3.1 (reproduced here as figure 7.5.2 for ease of reference) shows that although the choice of M&V option is less influential for client returns than for ESCO returns, it is one of the top 4 factors for each project. As might be expected, the relative influence of M&V option is closely related to the volatility of energy savings, the more volatile the energy savings, the most significant the choice of option.

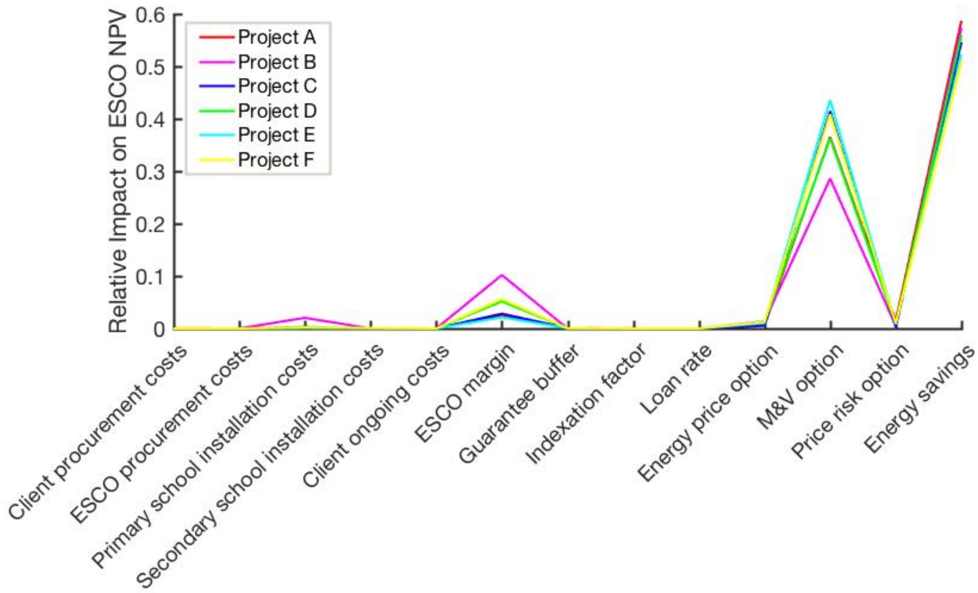


Figure 7.5.1: Sensitivity of ESCO returns to variance in input parameters

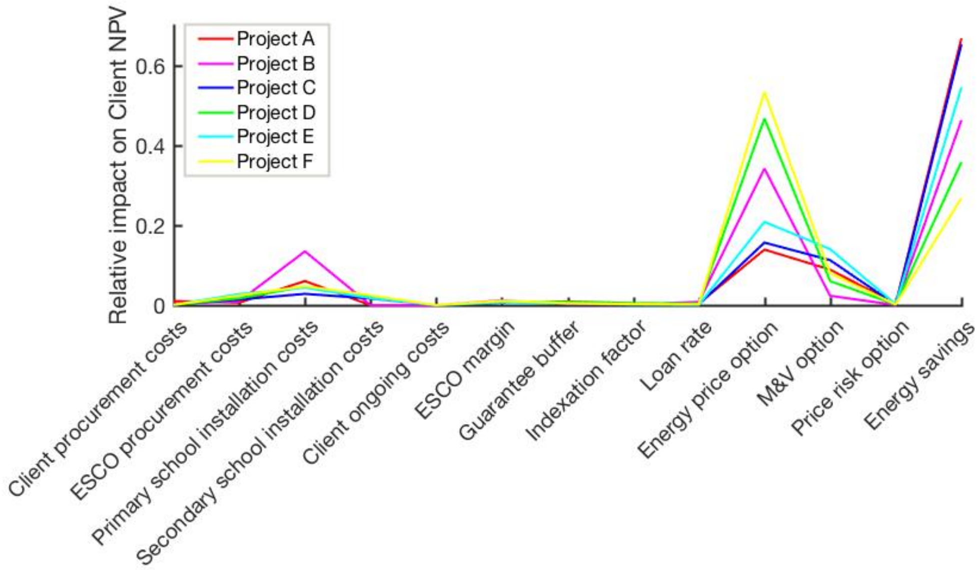


Figure 7.5.2: Sensitivity of Client returns to variance in input parameters

7.6 Support for hypothesis 2

Sorrell's [23] hypothesis that projects for which it is easiest to measure energy savings are most suited to out-sourcing through an energy performance contract prompted an exploration of the impacts of measurement and verification strategy on returns for Clients and ESCOs. However, the interview results presented in section 7.3 suggest that the ease or difficulty of measurement is related to the type of ECMs involved, making it unlikely that measurement ease (or difficulty) will be the determining factor in the success or failure of a project. A more detailed analysis of M&V approaches supports this. The results presented in this chapter suggest that ESCO monitoring and verification strategy preferences are largely driven by a desire to minimise risk exposure. This is a valid concern for ESCOs for two key reasons:

- ESCO returns are very sensitive to the choice of M&V strategy
- Gas savings are highly sensitive to operational factors which are likely to be beyond the control of the ESCO.

For clients, the choice of strategy has a smaller effect on overall project returns, this is largely due to the fact that even on an under-performing project, the client will be receiving some savings. Nonetheless, the sensitivity analysis results indicate clear value for the client in transferring risk to the ESCO.

For most projects with a fixed budget, there is a choice to be made between investing in additional monitoring and investing in additional energy savings, this means additional monitoring is likely to be unattractive for both clients and ESCOs. In addition, for additional monitoring to provide benefit, highly variable performance and operational parameters affecting savings must also be measured, more finely grained sub-metering alone will not provide this detail. While building management systems are capable of providing much of the detail required in the examples modelled here, an equivalent level of detail is also required for the baseline period.

Chapter 8

The Impact of Project Scale and Scope

8.1 Overview

Chapter 3 identified two further dimensions of Energy Performance Contracting projects which were expected to impact on the success of projects, in addition to transaction costs (discussed in chapter 6) and the ease of measuring savings (discussed in chapter chapter 7): their scale and scope. Sorrell [23] contrasted an ESCO for whom the provision of energy services is a core business undertaken for multiple clients and a client for whom energy services represent only a small part of business activities. Based on this, he identified three principle reasons why an ESCO would be able to deliver economies of scale in comparison with a single client.

- a greater ability to employ specialist resources by spreading the costs across a range of projects
- access to volume discounts through bulk purchasing
- standardisation and cost comparison between projects.

As a result, he proposed that the greater the scope of a project (the greater the range of energy services included in it) the more likely it was to be viable. He also proposed that the larger the overall savings the more likely a project would be to be viable. These hypotheses were echoed by the ESCO interviewees, several of whom spoke of two principle features of an attractive project: that it should either be a single site with very high energy consumption or a large number of very similar sites in which identical ECMs could be installed.

This chapter extends the evaluation of the hypothetical cases to explore the impact that project scale and scope have on financial returns for clients and contractors.

8.2 Evidence for the impact of project scale and scope

Sorrell [22] suggested that a lower value threshold would exist below which transaction costs would out-weigh potential savings. In later work, Nolden and Sorrell reported interviewees reporting a minimum annual utility spend of £500,000 [19] although they note that smaller companies might have a lower threshold for contract size. Pätäri et al. [83] found similar concerns amongst Finnish market participants regarding the scale of projects but suggested that these could be overcome by bundling smaller projects.

A number of the ESCOs interviewed commented on the minimum scale of project they thought necessary for viability, only one of these provided a value for the threshold (£1 million of installation costs). All ESCOs were asked only to provide transaction cost data for the case study projects that they would consider bidding for. The ESCO providing the threshold value indicated that they would not be prepared to bid for any of the projects. Although two other ESCOs also declined to provide cost data, they gave their reasons for doing so as concerns about commercial confidentiality. A second ESCO indicated that they would only bid for the two largest projects. These results match those of Nolden and Sorrell [19] and suggest that while there may be a minimum threshold, it is a subjective assessment for the individual ESCO.

The scale of projects is considered using different measures - Nolden and Sorrell [19] suggest a minimum threshold based on total baseline utility bills, Goldman et al. [28] reported that the average project size was £150 -200 $MJ/m^2/annum$ (indexed and converted to pounds sterling) and one of the ESCOs described a limit based on installation costs. It should be noted that by normalising energy savings with respect to floor area, Goldman et al.'s [28] measure is more accurately characterised as a measure of project scope since it measures the energy savings intensity rather than the size of the project.

8.3 Formulation of case study projects

Six case study projects were defined, based on the two underlying project archetypes, to allow pairwise comparison of project scale and scope. Three separate project scales were defined to cover the bulk of the range identified above and two separate scopes were defined, ECM sets 1 (lighting upgrade and heating controls) and 2 (lighting upgrade, heating controls, draught stripping, plant room insulation, boiler upgrade). As discussed in section 5.2.2, the validity of the scopes was verified with reference to RE:FIT project data and triangulated in client and ESCO interviews. Table 8.3.1 shows the project details according to the metrics identified above.

Table 8.3.1: Case study projects by measures of scale

Project	**Baseline Utility bill (£)**	**Annual energy savings ($MJ/m^2/annum$)**	**Installation costs (£)**
A	126,000	91	204,000
B	126,000	137	325,000
C	395,000	102	608,000
D	395,000	294	964,000
E	791,000	10	1,216,000
F	791,000	29	1,928,000

Comparison with the metrics identified in section 8.2 suggests that Projects A and B can be categorised as small in scale(below installation cost and utility bill thresholds) and E and F are large in scale (above the installation cost and utility bill thresholds identified), with projects C and D sitting closer to the thresholds.

Using Goldman et al.'s [28] energy savings intensity measure, projects A, C and E can be categorised as small in scope (falling below the lower end of the proposed range) and D and F as large (in excess of the upper end of the range). Project B is less clearly categorised since it is based only on the less intensively serviced primary school archetype and although clearly greater in scope than project A it is below the lower end of Goldman et al.'s range. For the purposes of this study it is included in the classification of larger scope projects.

8.4 Balance of transaction and production costs

Sorrell's [23] hypothesis of increasing project viability with scale was based on an assumption of increasing returns to scale. Interview responses from Clients and Contractors suggest that this may not be the case as the cost of developing baseline information is the most significant element of procurement costs and this was expected to scale with both the number of sites and the number of ECMs. Comparing the ratio of transaction costs to production costs for Client and ESCO for each project as shown in figure 8.4.1, suggests mixed results. For ECM set 1 this effect is small for the ESCO but for the clients the effect of a change in scale from small to medium is much greater. For ECM set 2, both client and ESCO show a large shift for a change in scale from small to medium but little change for a shift to medium to large.

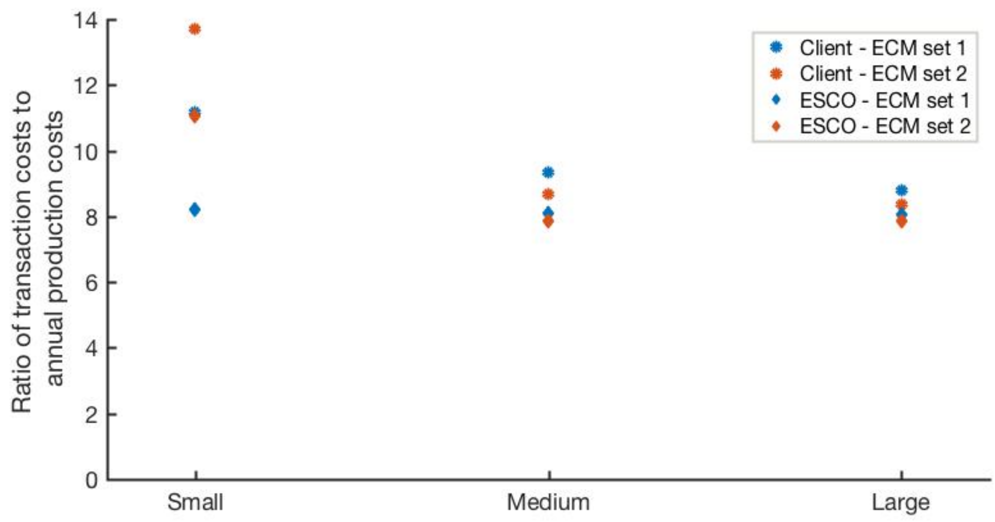


Figure 8.4.1: Ratio of transaction costs to production costs

8.5 Calculating financial returns

Ye and Tiong [116] categorised the wide range of methods that exist for evaluating the financial impacts of investment as:

- Methods based on return e.g. payback, rates of return, Net Present Value (NPV)
- Methods based on risk e.g. credit agency rating systems
- Methods based on risk and return e.g. Capital Asset Pricing Model, mean variance, utility theory, cumulative distribution theory.

The NPV-at-risk method was proposed, which has the advantage of taking into account both financing risks and project-specific uncertainties, as well considering the time value of money and establishing clear decision criteria. The distribution of NPVs over the range of project uncertainties is calculated using the weighted average cost of capital to determine the discount rate. Project risk can be measured by the proportion of the distribution which does not meet this threshold. Ye and Tiong [116] demonstrated the benefits of their NPV-at-risk method with a case study. Their approach was selected as the most appropriate method for this study since it allows stochastic uncertainties to be accommodated, thus combining a consideration of sectorial risks through the choice of discount rate and project specific uncertainties through stochastic variation. Another key attraction of the approach is that the NPV approach is the primary criterion by which government action can be justified [104]. As an extension of the classical NPV approach, the NPV-at-risk method should be easily understood by stakeholders familiar with the classical NPV approach.

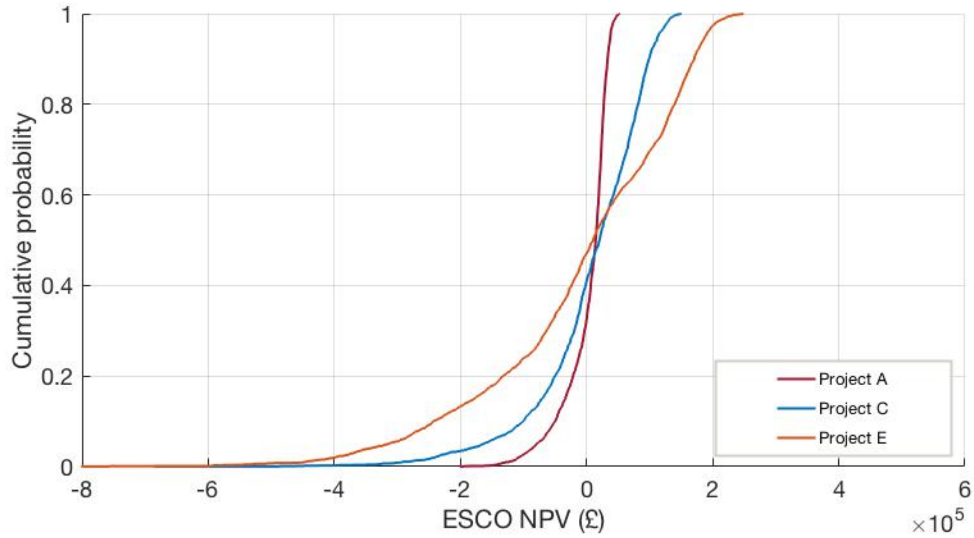
Although the NPV-at-risk approach overcomes a key limitation of the NPV approach with a transparent approach to assessing risk, it remains subject to the criticism that it "makes the false assumption that the investment is either reversible or that it cannot be delayed" [194]. In this study, the underlying assumption is that there is a significant opportunity cost to foregoing consumption and consequently the lost option value is zero. This is considered a valid assumption for small public sector projects, competing for scarce funding.

The NPV-at-risk method also makes two critical assumptions: the discount rate (discussed in section 4.7.2) and project term. Project term is particularly significant for this study since clients will continue to benefit from energy savings beyond the project guarantee period. As a result Ye and Tiong's method is extended to show the impact of the project term over which the NPV is evaluated, this is consistent with government guidance which suggests that costs and benefits should be evaluated over the useful life of the assets [104].

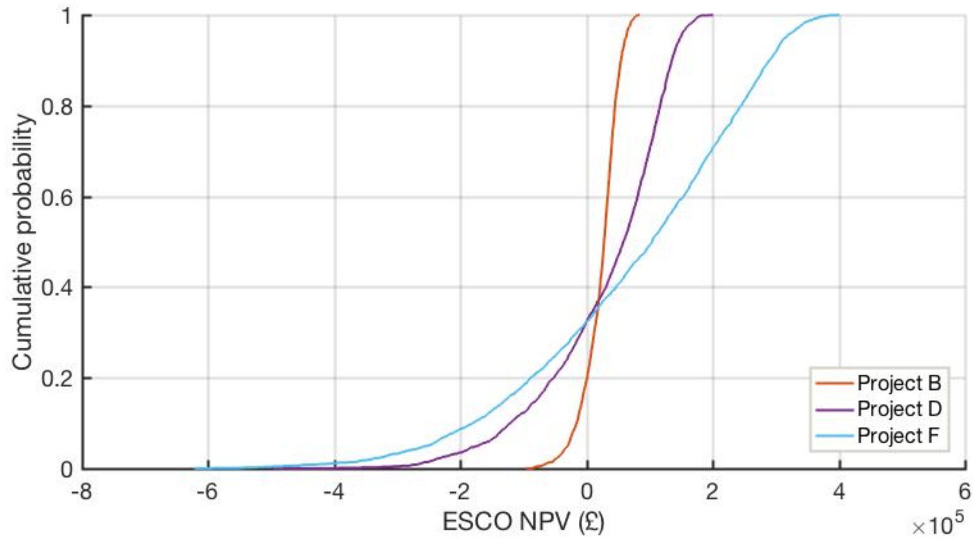
In contrast to the Client, the ESCO's involvement in the project ends at the expiry of the guarantee period, as there are no cash-flows to or from the ESCO following end of the guarantee period, the term over which the project is evaluated has no impact provided it includes the full guarantee period. Accordingly, ESCO returns are evaluated over a single project term - 9 years.

8.6 ESCO risk and reward

The resulting NPV distributions and risk levels are shown in figure 8.6.1 and summarised in table 8.6.1. In each case, the at-risk threshold was taken to be an NPV of zero based on equations (3.4) and (3.5) which define the minimum threshold for a project to be viability as a net zero income for both client and ESCO.



(a) ECM set 1



(b) ECM set 2

Figure 8.6.1: Distribution of ESCO returns for the two ECM sets

The results shown in table 8.6.1 highlight the relatively high risk levels for the projects in comparison with the decision threshold of 5% proposed by Ye and Tiong [116]. This should not be taken as suggesting that the projects would

Table 8.6.1: Proportion of NPV at risk for ESCO in each project

Project	ECM set	NPV-at-risk: ESCO (9 years)	Coefficient of Variance	Mean return (£)
A	1	32.35%	24.99	1,000
C	1	41.05%	13.40	7,000
E	1	47.05%	17.42	-9,000
B	2	19.50%	1.25	23,000
D	2	32.35%	3.41	30,000
F	2	32.35%	2.46	74,000

automatically be rejected since this value appears to have been selected based on its similarity to the 95% confidence interval rather than on any empirical evidence of decision thresholds in practice. In addition, Ye and Tiong's [116] case study is of a single very large power station project where a project failure could have a very significant impact on the contractor's balance sheet. For much smaller projects, ESCOs would be expected to take a less risk averse approach since the ability to enter into multiple different projects with different risk profiles would allow risks to be balanced across a portfolio of projects. Nonetheless, even with a significantly relaxed threshold of 20%, only project B would meet the decision criterion for ESCO investment.

It is also clear from figure 8.6.1 that for both ECM sets, the ESCO risk of a negative return is increased with increasing project scale. However, this is potentially counter-balanced by the greater spread of results as project scale increases meaning that larger positive returns are also possible.

Mills et al. [35] propose using the coefficient of variance (standard deviation of a set of results divided by the mean) to compare uncertainties of returns from different investments. This highlights the difference between the two sets of ECMs with the two-ECM set (set 1) being relatively unattractive due to high volatility and low returns; in contrast the volatility of the largest set of ECMs (ECM set 2) is an order of magnitude lower and returns are significantly higher.

Increasing scope and increasing scale would both be expected to reduce project volatility [35] due to the portfolio effect since the energy savings for individual buildings and ECMs are assumed to be independent and uncorrelated. It is clear from 8.6.2 that the portfolio effects of increasing project scale are not sufficient to offset the lack of diversity within the ECM set and that the balance of risk and reward for the ESCO is much improved by increasing the number of ECMs considered. Both ESCO and Client results are very strongly

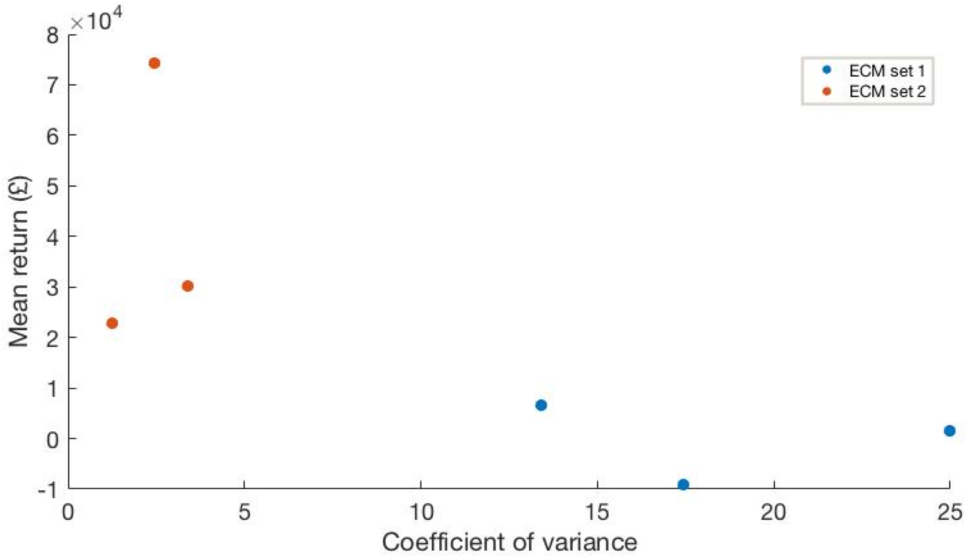


Figure 8.6.2: ESCO risk vs reward

influenced by energy savings. However, for ESCOs, this is an asymmetric risk, since they do not benefit from excess savings but only suffer penalties if the savings are below the threshold. Since the impact of the uncertainty in energy savings is greater than the impact of the uncertainty in transaction costs as shown previously in figure 6.3.2, increasing project scale increases the energy savings and thus the potential for a negative return.

The hypothetical project approach used in this study may have some influence on these conclusions. In practice, real school estates might be expected to be more diverse than the hypothetical project groupings explored in this study meaning that the results here may under-estimate the spread of actual results. However, since this study is constrained to explore aleatory and epistemic uncertainties associated with the ECMs applied and not failures or errors in installation, the effects of a group of installation measures installed at the same time, by the same contractor are effectively already accounted for in the framing of the study.

8.6.1 Client risk and reward

As noted previously, the impacts for clients are strongly influenced by the project term over which the NPV is evaluated, increasing term reduces risks. The risk of an unviable project is highest for the smallest scale projects and the smallest scope, with returns increasing as either project scale or scope increases. However, while the volatility of returns is lower than for the ESCOs, the pattern across the projects is less clear with the medium scale projects (C and D) having the highest coefficients of variance.

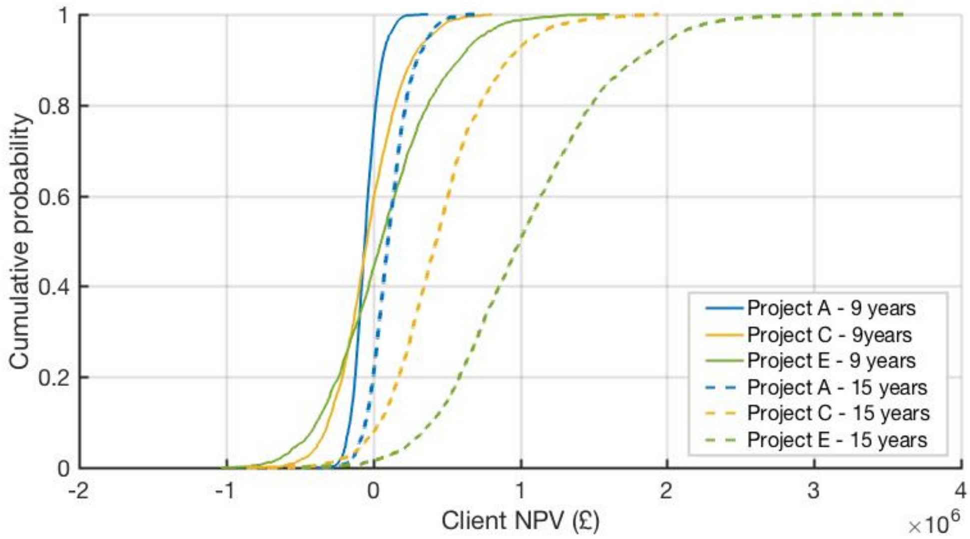
Table 8.6.2: Proportion of NPV at risk for Client in each project

Project	ECM set	NPV-at-risk 9 yrs (15 yrs)	Coefficient of Variance 9 yrs (15 yrs)	Mean return (£) 9 yrs (15 yrs)
A	1	73.20% (19.50%)	1.80 (1.23)	-50,000 (116,000)
C	1	58.75% (7.70%)	8.46 (0.78)	-27,000 (459,000)
E	1	43.65% (1.45%)	4.87 (0.52)	77,000 (1,049,000)
B	2	62.30% (9.30%)	3.42 (0.80)	-33,000 (219,000)
D	2	45.75% (1.15%)	5.37 (0.55)	58,000 (827,000)
F	2	40.15% (0.10%)	2.80 (0.47)	205,000 (1,764,000)

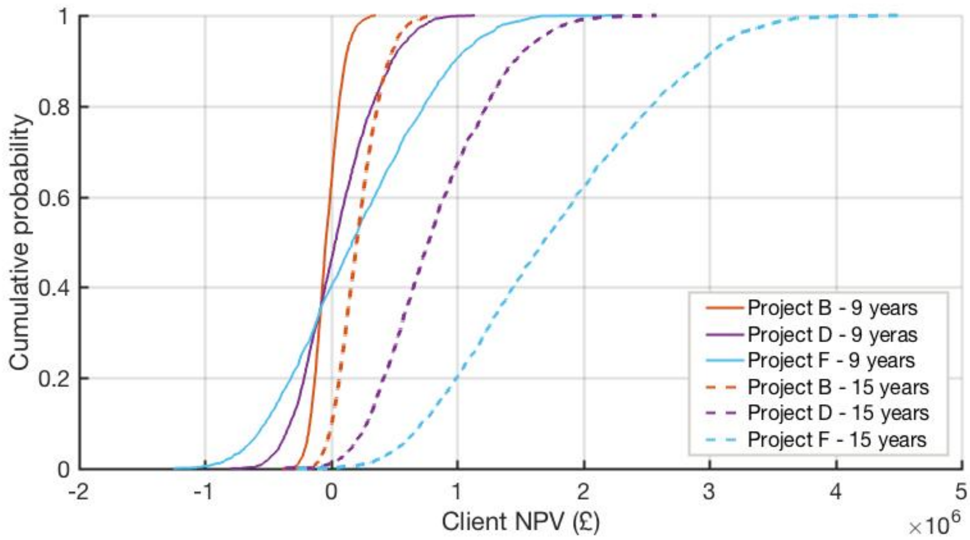
In contrast with ESCO results, increasing project scale and scope have similar impacts on reducing risks and increasing returns.

8.7 Changing risk allocation

The risk of an viable project for is likely to be unacceptably high for the ESCO based on the results in 8.6.1, where only project B appears to achieve even a 20% threshold. This makes it necessary to explore the impact of transferring risk from client to ESCO to determine if a more balanced risk profile can be achieved. The sensitivity analysis results presented previously in 6.3.2 suggest that the ESCO results are sensitive to M&V approach. Transferring M&V option risk means fixing option A as the chosen M&V option. In effect this choice places all energy savings risks with the client since as detailed in section 7.4.2 “measured” savings will be identical to guaranteed savings using



(a) ECM set 1



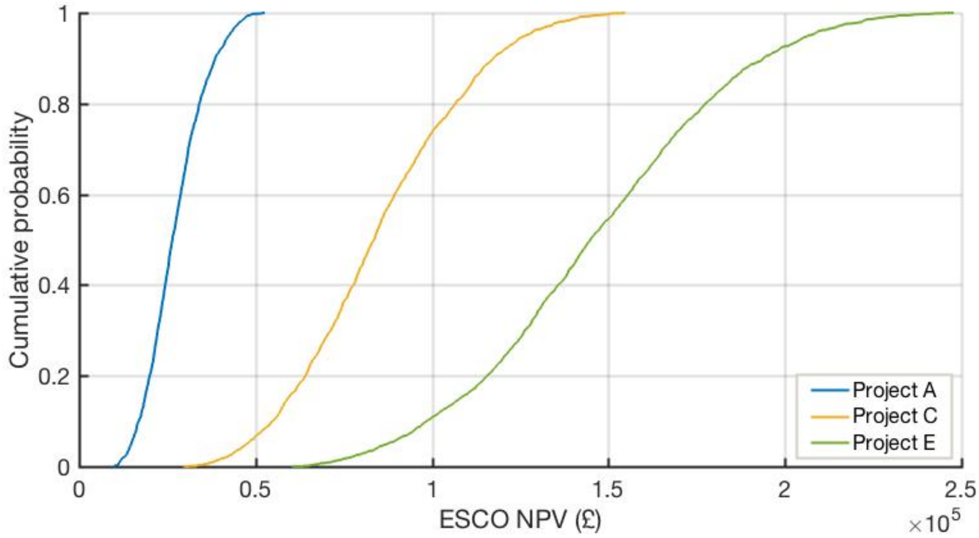
(b) ECM set 2

Figure 8.6.3: Distribution of Client returns for the two ECM sets

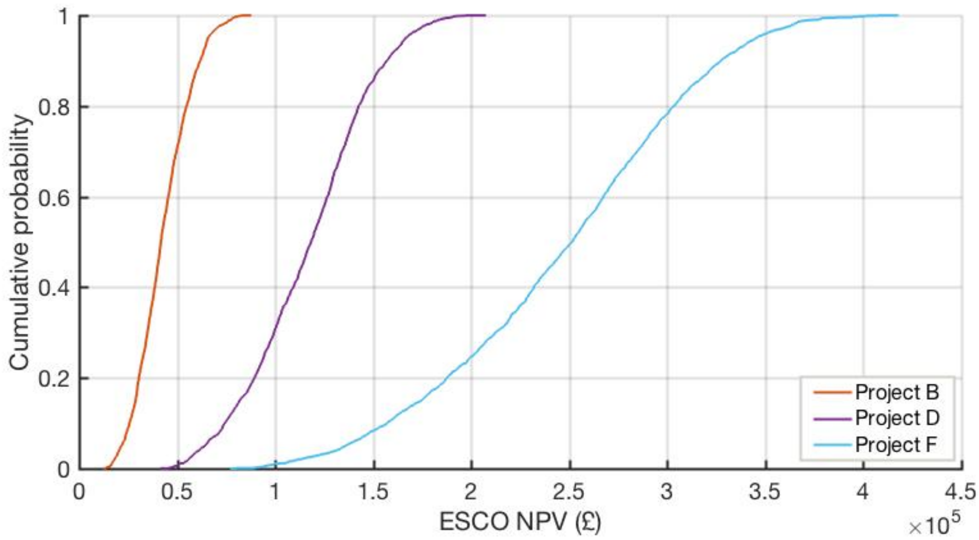
this approach. Tables 8.7.1 and 8.7.2 repeat the analysis of tables 8.6.1 and 8.6.2 with the M&V option fixed at Option A.

8.7.1 Effect of changing risk allocation on ESCO returns

The effect on ESCO returns is dramatic as can be seen in figure 8.7.1 and summarised in table 8.7.1 below. Fixing the M&V option transfers all energy sav-



(a) ECM set 1 with Option A M&V



(b) ECM set 2 with Option A M&V

Figure 8.7.1: ESCO returns with M&V fixed at Option A

ings risk to the client ensuring that ESCO returns are always positive. Project volatility (measured by coefficient of variance) is also significantly reduced and clear division between the two project scopes is no longer seen.

Table 8.7.1: Impact of fixing M&V option on ESCO returns

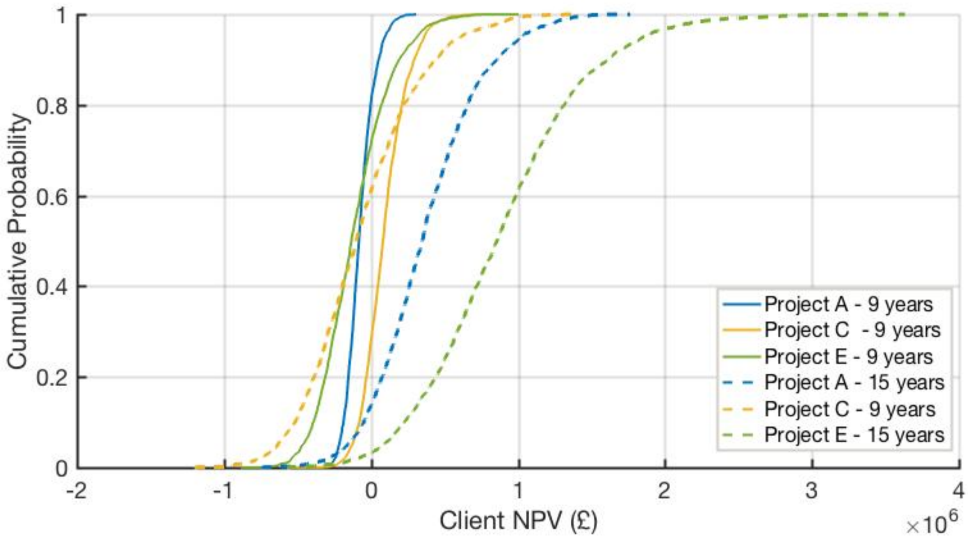
Project	ECM set	NPV-at-risk: ESCO (9 years)	Coefficient of Variance	Mean return (£)
A	1	0	0.30	27,000
C	1	0	0.28	85,000
E	1	0	0.24	146,000
B	2	0	0.32	43,000
D	2	0	0.26	117,000
F	2	0	0.26	246,000

8.7.2 Effect of changing risk allocation on Client returns

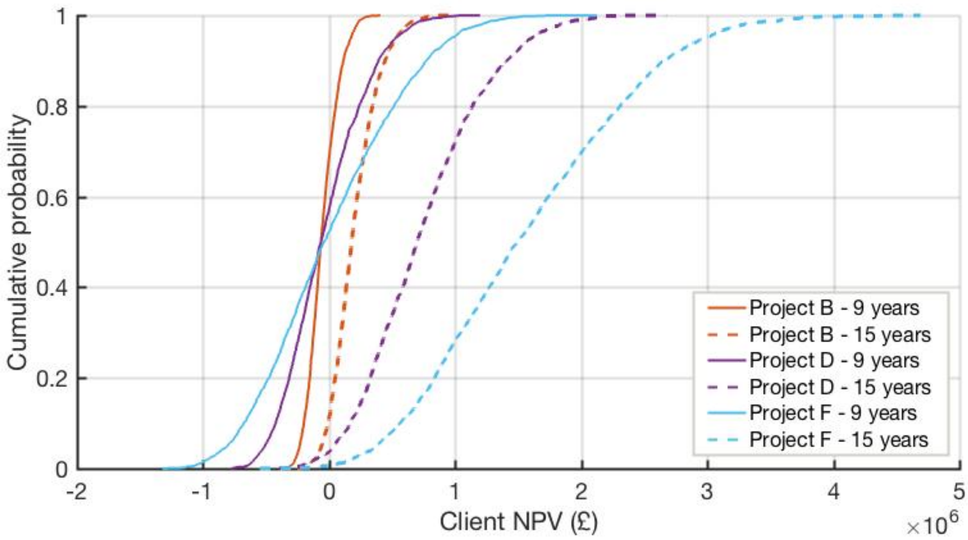
Transferring all energy savings risk to the Client would be expected to have a negative impact on Client returns. Figure 8.7.2 demonstrates this with mean returns for all projects being negative over 9 years. Project volatilities are broadly similar, the exception is for Project F which has a dramatically increased coefficient of variance, however, this results from a mean return which is relatively close to zero rather than from an intrinsic increase in volatility. However, for all projects, the position improves significantly when the evaluation period is extended. Viewed over the longer evaluation period, the increase in risk for the client and reduction in returns may be considered acceptable since a project will only be viable if both parties expect to at least break even. For the first ECM set, however, this conclusion is less likely with a mean forgone return of between 15% and 20%. For the second ECM set, this conclusion is perhaps more palatable with a mean forgone return of between 8% and 11%.

Table 8.7.2: Client returns with fixed M&V Option

Project	ECM set	NPV-at-risk 9 yrs (15 yrs)	Coefficient of Variance 9 yrs (15 yrs)	Mean return (£) 9 yrs (15 yrs)
A	1	80.60% (27.80%)	1.26 (1.61)	-75,000 (93,000)
C	1	71.20% (13.70%)	2.06 (0.96)	-114,000 (375,000)
E	1	61.00% (3.10%)	5.52 (0.61)	-37,000 (893,000)
B	2	68.85% (11.35%)	2.34 (0.90)	-52,000 (200,000)
D	2	57.30% (3.75%)	8.63(6.44)	-114,000 (744,000)
F	2	52.30% (0.70%)	43.65 (0.52)	13,000(1,571,000)



(a) ECM set 1 with Option A M&V



(b) ECM set 2 with Option A M&V

Figure 8.7.2: Distribution of Client returns with M&V fixed at Option A

Table 8.7.3: Impact of fixing M&V option on Client returns

Project	**ECM set**	**Δ NPV-at-risk** 9 yrs (15 yrs)	**Δ CV** 9 yrs (15 yrs)	**Δ Mean return** 9 yrs (15 yrs)
A	1	7.40% (8.30%)	-0.54 (0.38)	-50.46%(-19.23%)
C	1	12.45% (6.00%)	-6.39 (0.18)	-321.15% (-18.37%)
E	1	17.35% (1.65%)	0.65 (0.09)	-189.51%(-14.81%)
B	2	6.55% (2.05%)	-1.07 (0.09)	-59.05%(-8.54%)
D	2	11.55% (2.60%)	3.26 (0.09)	-163.87%(-10.08%)
F	2	12.15% (0.60%)	40.85 (0.05)	-93.83%(-10.98%)

8.7.3 Comparison with traditional procurement approaches

The existence of an intermediate procurement option was noted in section 3.4. In this scenario, the client undertakes a traditional procurement exercise for the installation of the ECMs. Since no performance guarantee is required, the set of potential installers is larger and alternative procurement frameworks can be used. ECMs might also be procured individually rather than aggregated into a single project as in the EPC option. As a result, transaction costs for contractors and clients have the potential to be very different to those which result from an EPC procurement, making a direct comparison impossible without the collection of considerable additional data. Although unknown, since the pool of contractors is larger, the financial risk to the contractor the same or smaller and the procurement process need only test the works element of the project, transaction costs would be expected to be lower for a traditional procurement than for an EPC approach and thus a transaction cost premium is paid for an EPC procurement.

It follows that for an EPC approach to be worthwhile, the likely expected benefit of the performance guarantee must be greater than the EPC transaction cost premium. The results presented in table 8.7.3 which highlight the financial return forgone if the performance guarantee is removed provide this detail. The difference in mean return being the benefit derived from the EPC and setting an upper limit for the transaction cost premium paid for the EPC route.

8.8 Support for hypotheses three and four

Chapter 3 drew on Sorrell's [23] earlier work to establish the hypotheses that projects with a larger scope of energy savings would be more likely to be viable than those with a smaller scope (hypothesis three), and that large projects would be more likely to be viable than small (hypothesis four). The results in this chapter built on the results of the previous two chapters to test these hypotheses.

8.8.1 Impact of project scope

According to Sorrell [23], increased project scope means greater energy savings and consequently, greater returns. This effect is borne out by these results with the pairs of projects at each scale option showing greater returns for the larger ECM set (set 2). While the portfolio effect is typically considered at a project level [35], it also applies at the level of an individual site where the inclusion of a larger number of ECMs allows for balancing of surpluses and shortfalls in energy savings achieved by individual ECMs. As a result, project volatility is lower for the larger ECM set at scale option.

8.8.2 Impact of project scale

Sorrell hypothesised that ESCOs would bring benefits of economies of scale to project and that this would be more pronounced for larger scale projects. The data collected for this project suggests that this effect is not great. Interview results suggest that survey costs are a significant element of transaction costs and the ratios of transaction costs to production costs are broadly consistent across the projects studied.

A more significant driver for the impact of project scale comes from the portfolio effect [35], in this study it is assumed that the results for each ECM on each site are independent and uncorrelated. Consequently, increasing project scale results in increasing diversity and reduced volatility as ECMs and projects with lower returns are balanced out by those with higher returns. In practice, there may be some correlation between the results of the same ECMs, installed by the same ESCO on different buildings. This would mean a reduced benefit from increasing project scale as it would not increase diversity to the same extent. While the results for Client returns provide support for hypothesis four, those for the ESCO do not: for both project scopes, increasing project scale results in increasing risk of an unviable project. This is due to the asymmetry of the energy risk sharing mechanism in the RE:FIT contract studied here coupled with the complexity of the governance arrangements. ESCO returns are only negatively impacted by energy savings as there is no sharing of excess savings and surplus savings on one site cannot be used to off-set those on another. This, coupled with the dominant effect of energy savings on ESCO returns, means that as project scale increases, so do energy savings and consequently so does the probability of savings shortfalls. It seems likely that a symmetric sharing mechanism would remove this effect but further work would be necessary to explore this.

The risk balancing effects of increasing project scope are greater than those of project scale in the projects investigated here. For Clients and especially for ESCOs, increasing project scope is more likely to result in a viable project than increasing project scale.

8.9 Suitability of the case study projects for EPCs

Viewed over the longer term, the prospects of a successful outcome for the Client in each of the projects is very good as highlighted by figure 8.6.3. However, for ESCOs, the prospect of a negative outcome due to overall project uncertainties is likely to be unacceptably high. As figure 8.6.1 shows, increasing project scale exacerbates the situation. Although increasing project scope reduces the prospect of negative returns, this is unlikely enough to be make projects more attractive. Three possible options to address this issue are:

- **Reduce uncertainty** - as discussed in section 7.6, additional could be used to target the most significant uncertainties, this monitoring would need to be focused on those aspects which are responsible for the largest uncertainties. This additional monitoring comes at a cost and would also need to be applied to the baseline conditions which could create a delay in project delivery while data was collected.

- **Reduce risk transfer** - restricting measurement and verification to Option A means limiting the ESCO's risk to that arising from the failure of an ECM, consequently, in the absence of equipment failure ESCO returns are always positive as shown in figure 8.7.1. Although long term Client returns are reduced by between 8 and 19%, they remain positive. However, although this analysis suggests that this change in risk allocation is a viable option, it is only part of the picture. Selecting Option A limits the risk taken by the ESCO to that undertaken in a standard installation contract. As discussed in section 7.4.2, an EPC will, in principle, be more expensive than a standard installation contract and the margins suggested by ESCOs for the EPC contracts in the range of 5 - 20% may also be higher. Unless there is a substantial difference in risk transfer between an EPC and a standard installation contract, the EPC represents poor value for the Client.

- **Alternative contractual mechanisms** - the high level of risk for the ESCO is partly driven by the combination of an asymmetric guarantee mechanism and the complexity of control in the client organisation. Since the guarantee is applied at the level of the individual school (necessary since the school is responsible for the utility bill) and the ESCO does not share in any excess savings, there is no possibility of balancing under-performance on one site with over-performance on another. Allowing calculation of the guarantee at a project level or introducing some sharing of excess savings at the site level would off-set this and reduce the potential for negative ESCO returns.

Chapter 9

Conclusions and Recommendations for Future Work

9.1 Overview

The analysis of the existing literature relating to energy performance contracts set out in Chapter 2 established the significance of energy performance contracting as a mechanism for increasing energy efficiency investment. However, it was also clear from this review, that despite global interest in EPC, most commentators agreed that markets worldwide had failed to achieve their potential and a range of reasons were proposed to explore this. The bulk of the literature on EPCs has focused on market-level factors: however, even in jurisdictions such as the UK, with a favourable procurement environment and active government support, market growth still lags behind expectations. The aim of this study has been to explore how the elements of an individual project contribute to its potential for success in an attempt to understand how projects might be structured to make them more likely to be successful for both Client and contractor (ESCO) and thus increase the attractiveness of the market.

Since the decision to procure an energy performance contract can be framed as an outsourcing decision, Chapter 3 considered alternative theoretical frameworks which have been proposed to explain governance structures. Transaction cost economics was selected as the most suitable approach for exploring alternative project structures. Sorrell's [22] work pointed to 4 key hypotheses about how project structure would affect project viability:

- **Hypothesis 1**
  Market competitiveness - a more competitive market will result in lower transaction costs and thus increase the viability of EPC projects

- **Hypothesis 2**
  Task complexity - the easier it is to measure and verify changes in energy consumption the more likely a project is to be viable

- **Hypothesis 3**
  Technical potential for production cost savings - an EPC project is more likely to be viable when the range of energy conservation measures included is large

- **Hypothesis 4**
  Aggregate production costs - increasing the size of a project by increasing the number of facilities included in it increases the likelihood of viability.

Chapters 4 and 5 detailed the modelling framework used to test these hypotheses and how data for transaction costs and production costs were gathered and developed. Chapters 6, 7 and 8 present the results for transaction costs, production costs and finally for overall financial returns for both Client and ESCO and discuss the implications that these results have for the 4 research hypotheses. This concluding chapter draws these results together to set out the key findings of this study. The overarching limitations of the current study are also considered with consequent suggestions for future work.

9.2 Hypothesis 1 - market competitiveness

The first hypothesis proposed that a more competitive market would result in lower transaction costs. However, the results presented in chapter 6 did not provide strong support for this hypothesis. Real world transaction cost data from procured projects was not available: however, data on project scale and number of bidders was. This data showed no relationship between project scale and the number of bidders. The transaction cost data collected from ESCOs on the hypothetical case study projects showed that the smaller projects were less popular than the medium and large projects. However, the projects were still attractive to 6 of the 8 ESCOs who provided transaction cost data. The ratio of transaction costs to production costs was higher on these projects for both ESCOs and Clients, although this was mainly due to higher installation costs. Margins were not significantly different between the different projects. As a result, it can be concluded that within the relatively narrow market sector considered here, the competitiveness of different projects is relatively similar and there is little impact on transaction costs as a result.

There was clear evidence that the hypothesis had been interpreted in reverse in procurement: reducing transaction costs would lead to increased competition for projects. Procurers had evidence of projects where procurement had been attempted twice, once in a format with relative high costs at risk to bidders resulting in little market interest, and subsequently in a format with reduced costs at risk which resulted in a larger number of bidders. However, it was clear from the results of client interviews that the lower cost-at-risk approach led to a much lower level of cost information being tested in competition. As a consequence, clients incurred increased policing and enforcement costs meaning that the overall level of transaction costs to the project may well not have been reduced.

9.3 Hypothesis 2 - task complexity

The difference in production costs between the do-nothing option and the EPC option is the result of the energy savings arising from the implemented energy conservation measures. Chapter 7 explored the range of energy savings which resulted from each project and considered the different approaches to measuring the energy savings. The second hypothesis stated that the projects would be more likely to be successful when it was easier to measure energy savings as this would reduce the complexity of the contracts required. Evidence from the literature agreed with interview results which suggested that savings are generally measured either on a whole building basis or using spot measurements. The level of performance risk passed to the ESCO by these two approaches is very different and sensitivity analysis results demonstrated a significant impact on ESCO returns. The level of impact on Client returns is also significant but to a lesser degree.

Measurement approaches based on ongoing measurement of the retrofit impact or energy modelling are less popular due to their higher cost. Further sensitivity analysis of the energy modelling results highlighted the importance of measuring the parameters which allow responsibility for energy consumption to be allocated between the parties. The importance of the set of operational parameters such as temperature set points, hours of operation etc. was clear. Although the three measurement approaches considered gave different results, none allowed a detailed understanding of responsibility for energy consumption, allocating all responsibility to one or other of the parties. Given the significance of the approach to measuring savings, it was concluded that the ease of measuring savings is likely to be critical to the success of a project but that the hypothesis might be better expressed as the " the easier it is to measure **each party's responsibility** for energy consumption, the more likely a project is to be successful". However, to achieve this allocation of responsibility, new measurement approaches are needed. A key element of this is a better understanding of occupancy-related factors. While school building occupancy may be seen as superficially well defined, in practice buildings are in use for many more hours that the formal school day. For example, a recent analysis of 5 UK school buildings revealed around 50% of electrical energy was used outside the school day [195]. The work being undertaken to develop occupancy modelling techniques as part of IEA Annex 66, [196, 197][for example] offers the potential for better understanding of baseline occupancy parameters. However, such additional monitoring will, inevitably, entail additional costs which may have the potential to affect project viability.

9.4 Hypothesis 3 - Technical potential for production cost savings

Hypothesis three proposed that an EPC project is more likely to be viable when the range of energy conservation measures included is large. This hypothesis was tested by comparing two different project scopes at a range of different project scales. The results presented in tables 8.6.1 and 8.6.2 clearly demonstrate the reduction in volatility for the both ESCO and Client returns which results from the inclusion of additional ECMs in the second ECM set (Projects B, D and F).

9.5 Hypothesis 4 - Aggregate production costs

Hypothesis four suggested that increasing project scale would increase the viability by increasing potential for production cost savings. Similar reasoning was applied by Pätäri et. al [83] who suggested bundling smaller projects to make them more attractive to the market. Although the results presented in table 8.6.2 support this hypothesis, those shown in table 8.6.1 do not. This appears to be due to two interlinked factors - the governance structure means that guarantee performance is evaluated at the level of the individual school and the asymmetric sharing mechanism means that there are no surpluses from over-performing sites to off-set shortfalls on under-performing ones. Consequently, increasing scale can only increase risks of negative returns for the ESCO.

9.6 Overall viability of projects

Transaction and production cost results were combined in Chapter 8 to explore the overall impact on financial returns for Clients and ESCOs. While the longer term outcomes for Clients had a high probability of being positive, for ESCOs the possibility of a negative return was very high. ESCO returns were dramatically improved when the bulk of performance risk was removed. Client returns were reduced as a result but an additional deleterious effect is the over-payment which the Client has in effect made for a level of protection which is not, in fact delivered through the contract.

9.7 Implications for policy makers and project stakeholders

The International Energy Agency's 2016 Energy Efficiency Market Report [198] suggests a global market for ESCO activities of $24 bn in 2015. While the figure for EPC projects as defined in chapter 2 will be lower than this, it is clear that a substantial volume of EPC projects are undertaken worldwide each year. Since only a third of estimated potential energy efficiency projects have been undertaken to date [198], the bulk of research effort has focussed on how these activities can be expanded, rather than on the outcomes of the projects actually undertaken. This is a particularly important gap in the UK context since it has not been filled by detailed government guidance. General procurement guidance is available in the form of the Treasury's Green Book [104] which sets out guidelines for appraisal and evaluation in central government but this guidance is necessarily broad in nature and relates to large central government procurements rather than the smaller exercises undertaken by local government in an EPC context.

The clear emphasis of the Green Book guidance is on exploring all possible possible procurement options and clearly identifying the potential costs, benefits and risks associated with each. In this study, by undertaking detailed modelling of a carefully specified range of hypothetical projects, together with analysis of existing project data, a number of new insights have been gained. These insights enable the implications of different options (such as the choice between target and partner bids) to be seen more clearly contributing to more effect review of options prior to procurement commencement.

9.7.1 Procurement approaches

For ESCOs selecting bidding opportunities, bidding costs at risk are a significant factor and reducing design requirements at bid stage will have a significant impact. As highlighted by Bajari and Tadelis [178], although this approach can be beneficial for complex projects which cannot be fully specified due to their complexity, it increases administrative burdens for clients. However, the RE:FIT project data reviewed suggests that the partner bid approach, with its reduced requirement for upfront design, is more likely to be used on smaller projects. For these projects the burden of additional policing and enforcement costs can be significant.

9.7.2 Structure of the guarantee

The asymmetric sharing mechanism in guaranteed savings contracts such as the RE:FIT contract studied here, coupled with the governance arrangements which result from bundling a series of independent bill-payers together, results in projects with high probabilities of negative returns for ESCOs. This factor is likely to result in reduced market interest over the longer term. This is a more significant issue for projects with smaller numbers of measures since there is less scope for balancing effects. This suggests that a performance contract is ill-suited to projects with very small numbers of measures and that unless a mechanism exists to allow the ESCO to spread its risk across a bundle of projects, bundling will simply increase risks. Such a mechanism could be achieved either by introducing a shared savings approach, allowing the ESCO to benefit from surplus savings, or by assessing the guarantee at a project level. Of these two possibilities, the former is likely to be more workable in practice since it maintains the clear separation between distinct organisations each responsible for their own budget.

A further potential advantage of a shared savings approach is the change in the balance of incentives. The guaranteed-savings contract is a fixed price contract which creates the incentive for cost reduction by the ESCO in an attempt to maximise their returns [178]. A consequence of this is the potential for dilution of quality in order to achieve a reduction in costs. Although the performance guarantee is intended to provide protection for this, the potential for the guarantee to be watered down and to provide less protection than the client expects is high as highlighted in chapter 7. In contrast, a shared savings model in which the ESCO benefits from potential surplus savings, creates an incentive to maximise savings and increases the incentive to accurately measure savings.

9.7.3 Alternative procurement approaches

From the perspective of the client, the value of an EPC procurement lies in the risk transfer to the ESCO. As highlighted in section 8.7.3, a conventional procurement is likely to be less expensive than an EPC, hence an EPC is an appropriate route only if the increased procurement costs (the "EPC premium") are expected to be lower than the financial benefit of the risk transfer. This suggests that even for projects where the NPV at risk is acceptable to clients, the EPC premium must be lower than the forgone benefit of the risk transfer. For projects E, D and F which achieve an NPV at risk of less than 5% over a 15 year evaluation period, the value of the risk transfer ranges from £83,000 to 193,000 based on the change in mean return over the 15 year period.

9.7.4 Insights from sensitivity analysis

Global sensitivity analysis has played an important role in this study, allowing the factors which have the greatest impact on model outcomes to be highlighted. As a result, important considerations for the design of energy performance projects were highlighted:

- identifying the factors which contribute most to uncertainty in energy savings would permit additional investment in monitoring to be targeted at the areas where it would have most effect.

- the dominant effect of energy savings uncertainty on returns highlights the need to improve baseline data collection and also suggests how evaluation criteria could be targeted at areas in bidder responses which make the biggest difference to overall client outcomes. A key example of this is the ESCO's margin, which has a limited impact on Client returns in comparison with projected energy savings. For procuring organisations tasked with obtaining best value for money raised through taxation, weighting evaluation criteria in favour of bidders with lower stated on-costs is highly attractive. This is compounded by a drive to reduce the burden on bidders in the procurement phase which is likely to lead to less emphasis on the projected energy savings.

- the relative influence of procurement and transaction costs on overall outcomes suggests that the investment of additional transaction costs to improve baseline data would be beneficial since this would allow the overall project uncertainty to be reduced. As this would benefit ESCO as well as the Client, it may also have a beneficial impact on the number of bidders.

9.8 Principal limitations of this study and suggestions for further work

Any modelling study is an exercise in simplification and its results must be read in that light. The key simplifying assumptions made have been highlighted and justified in each section and are not repeated here. Instead, this section focuses on those assumptions and simplification which potentially have greater impacts and which cannot be easily tested without significant additional work.

9.8.1 Underlying building archetypes

This study was based on two building archetypes and 5 energy conservation measures, care was taken to define building fabric parameters to cover a wide range of potential building types. However, only one arrangement of building systems was used for each archetype and since sensitivity analysis results suggest these are influential parameters this may have resulted in an understatement of the diversity of energy savings possible. A similar comment can be made about the use of a single set of geometric inputs for each archetype: for example Victorian and Edwardian school buildings are common in London with floor to ceiling heights in excess of 4m. In future, it would be desirable to extend the current study to include a wider range of building archetypes.

9.8.2 Stochastic modelling

While baseline energy models are selected stochastically for this study in order to develop a distribution of energy consumption profiles, the models themselves are static. The considerable research effort currently underway to couple energy models with stochastic occupancy models offers the prospect of extending this work in future. However, such approaches are dependent on the validity of the underlying occupancy profile data and detailed data which currently does not exist would be required on occupancy profiles in schools to take this forwards.

9.8.3 Alternative contractual models

The results contained in this thesis are based on a single contractual model and its risk sharing options. While this is the primary mechanism through which energy performance contracts are procured in the UK schools sector, it is far from the only framework in use in the public sector. There are a range of different frameworks in use in the UK public sector [19], of these two are of particular interest due to the distinctly different guarantee mechanisms used:

- **Carbon and Energy Fund (CEF)** [199] - the CEF framework was developed for use within the UK health sector and the form of contract has its origins in NHS standard form drafting for Private Finance Initiative contracts. The performance guarantee takes the form of a shared savings guarantee with as savings pool created from surplus savings which is used to off-set shortfalls in subsequent years. Unlike the RE:FIT contract modelled in this study, which also allows some off-setting to take place, the CEF sharing mechanism allows for the savings pool to be shared between the client and ESCO once it passes a certain threshold.

- **Non-domestic energy efficiency (NDEE) framework** [200] - the NDEE framework was launched in 2016 and has more than one form of contract, the guaranteed savings framework is of interest since it is unlike the RE:FIT framework in which the ESCO receives payment for installation on completion of installation and the penalty for missing the performance target is directly proportional to the shortfall. The NDEE uses a retention mechanism instead in which energy savings are tested after a full year of operation, if savings are not achieved and rectification is not possible, the entire retention amount would be forfeited regardless of the scale of shortfall. As the NDEE programme is in its early stages, M&V had not been undertaken at the time of interview.

These mechanisms entail very different risk profiles for ESCOs and clients, which would be expected to impact on transaction costs. In future it would be important to extend the results of the current study by collecting additional transaction cost data to explore whether the results would remain consistent when the alternative guarantee mechanisms are employed.

9.8.4 Alternative measures of performance

Traditionally, energy performance contracts have focused on reductions in utility bills. However, as Demand Side Reduction strategies increase, it will be important to understand how the monetisation of reductions in consumption, in particular, during mandated time periods can be incorporated within the existing EPC frameworks. In this way, measures of performance might shift from annual energy consumption to number of hours in which consumption exceeded a specified target. A key challenge of extending the study in this direction is the impact of the change in granularity of timescale required for energy consumption and the challenges that this poses for BES.

9.8.5 Exploration of other industry sectors

The methods used in this study to explore the impact of a performance guarantee in the UK schools sector, have the potential to be extended to other sectors as well. An obvious initial extension would be to undertake a similar study for a hospital project but the application is not necessarily limited to the public sector. There are many other areas where similar analysis to this could be used to unlock the "golden triangle" of negative-cost efficiency and CO_2 savings. The portion of figure 9.8.1 [201] below the horizontal axis indicates the large number of industrial processes with currently un-realised potential for energy efficiency projects with positive financial returns. Currently, these improvements are not being made, owing to internal competition for capital and perceived risk of non performance. EPCs have the potential to unlock investment in energy efficiency in these sectors but to do so will require careful structuring of projects to avoid the pitfalls identified in this study.

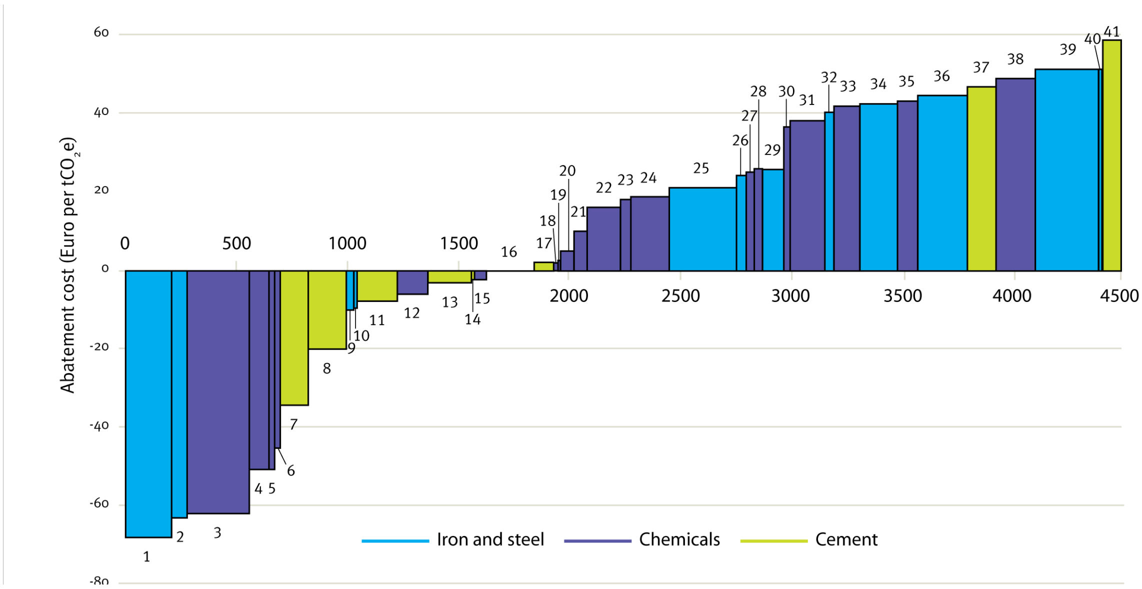


Figure 9.8.1: Potential for energy efficient investment in iron and steel, chemical and cement industries (reproduced with permission from the authors)

9.9 Summary

Despite the limitations detailed in section 9.8 above, this study presents a detailed examination of the application of a particular form of energy performance contract to a specific set of projects. The form of contract is in widespread use currently and the projects tested in this study are typical of those being undertaken using this form of contract. The results of this study suggest that

- not all of these projects are well-suited to this form of procurement. In particular, this study highlights the importance of having a wider range of energy efficiency measures

- more effective monitoring methods are needed focused on the collection of data which facilitates the allocation of responsibilities between the parties.

- reducing costs for competing bidders results in less market testing of prices which requires Clients to increase spending on policing and enforcement costs

- bundling smaller projects together cannot reduce risks for the ESCO unless there is a mechanism for balancing returns between individual projects.

Appendix A

DSCF Model code location

The DSCF model code has been uploaded to a private github repository: https://github.com/Papachama/Thesis-model-code

Please contact the author to request access.

Appendix B

Variable Parameters

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
Circulation occupancy levels	people/m^2	triangular	7.56E-02	9.45E-02		8.50E-02	[202]	based on pupil capacity and pupil:teacher ratio max is 1314 people, assume min is 20% lower due to lack of surplus spaces, maximum occupancy takes place for 10 mins each hour in reality but spread over whole hour for modelling purposes
Classroom occupancy levels	people/m^2	triangular	2.55E-01	5.82E-01		4.18E-02	[202]	london average is 21 pupils per class with pupil:teacher of 10.5. Max is 30 with 2 adults, assume symmetric minimum
Hall occupancy levels	people/m^2	triangular	2.22E-01	4.44E-01		3.33E-01	[203]	assembly hall/dual function for upper band, lower band from dining assume full occupancy is 20% of time

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
ICT occupancy levels	people/m^2	triangular	2.33E-01	5.33E-01		3.83E-01	[202]	see classroom occupancy notes
Kitchen occupancy levels	people/m^2	triangular	7.86E-02	2.03E-01		141E-01	[204]	assumed 1000 meals (scaled for primary school) and 6am to 2pm working hours
Office occupancy levels	people/m^2	triangular	6.64E-02	1.11E-01		8.85E-02	[205]	London occupancy density is 11.3m^2 per person assume min/max of 25%
Practical occupancy levels	people/m^2	triangular	1.75E-01	4.00E-01		2.88E-01	[202]	london average is 21 pupils per class with pupil:teacher of 10.5. Max is 30 with 2 adults, assume symmetric minimum
Toilet occupancy levels	people/m^2	triangular	2.65E-01	3.60E-01		3.10E-01	[206]	minimum and maximum taken from layouts
Classroom equipment levels	W/m^2	triangular	8.00E+00	1.20E+01		1.0E+01	[207, table 6.2]	

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
ICT equipment levels	W/m^2	triangular	2.10E+01	4.10E+01		3.10E+01	[208]	Variation from [209]
Kitchen equipment levels	W/m^2	triangular	3.9E+02	1.11E+03		7.49E+01	[153, table 8.6]	
Office equipment levels	W/m^2	triangular	1.00E+01	1.60E+01		1.3E+01	[210, table 12.2]	range is based on occupancy density
Practical equipment levels	W/m^2	triangular	2.10E+01	4.10E+01		3.10E+01	[208]	ICT values used due to lack of data
classroom lighting levels	W/m^2	triangular	1.20E+01	2.10E+01		1.65E+01000	[207, table 6.2], [149, p. 15]	minimum value taken from CIBSE guide A, maximum value taken from Philips
office lighting levels	W/m^2	triangular	8.0E+00	1.370E+01		1.09E+01	[149, p. 35]	minimum value taken from CIBSE guide A, maximum value taken from Philips
hall lighting levels	W/m^2	triangular	1.20E+01	1.30E+01		1.25E+01	[149, p. 27], [207, table 6.2]	

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
ancillary lighting levels	W/m^2	triangular	8.00E+00	1.00E+01		9.00E00	[149, p. 31], [207, table 6.2]	
intermittent heating set point	°C	triangular	1.60E+01	2.40E+01		1.90E+01	[209], [207, table 1.5]	CIBSE guidance is 19 - 21
regular heating set point	°C	normal			1.30E+00	2.06E+01	[211]	
kitchen heating set point	°C	triangular	1.50E+01	1.80E+01		1.65E+01	[207, table 6.2]	General building areas - kitchens used
intermittent heating set back temperature	%	triangular	9.60E+00	1.44E+01		1.20E+01	[212]	National Calculation Methodology value taken as mean with 20% band
regular heating set back temperature	%	triangular	9.60E+00	1.44E+01		1.20E+01	[212]	National Calculation Methodology value taken as mean with 20% band
kitchen heating set back temperature	%	triangular	9.60E+00	1.44E+01		1.20E+01	[212]	National Calculation Methodology value taken as mean with 20% band

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
general occupancy schedule – partially occupied starts am	time	triangular	5.00E+00	7.00E+00		6.00E+00	[212]	National Calculation Methodology value taken as mean with 1hr band
general occupancy schedule –fully occupied starts	time	triangular	7.00E+00	9.00E+00		8.00E+00	[212]	National Calculation Methodology value taken as mean with 1hr band
general occupancy schedule – partially occupied pm starts	time	triangular	1.50E+01	1.70E+01		1.60E+01	[212]	National Calculation Methodology value taken as mean with 1hr band
general occupancy schedule – partially occupied pm ends	time	triangular	1.70E+01	1.90E+01		1.80E+01	[212]	National Calculation Methodology value taken as mean with 1hr band
Kitchen occupancy schedule – on	time	triangular	6.00E+00	8.00E+00		7.00E+00	[212]	National Calculation Methodology value taken as mean with 1hr band

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
kitchen occupancy schedule – off	time	triangular	1.40E+01	1.60E+01		1.50E+01	[212]	National Calculation Methodology value taken as mean with 1hr band
general equipment on	time	triangular	7.00E+00	9.00E+00		8.00E+00	[212]	National Calculation Methodology value taken as mean with 1hr band
general equipment off	time	triangular	1.50E+01	1.70E+01		1.60E+01	[212]	National Calculation Methodology value taken as mean with 1hr band
kitchen equipment on	time	triangular	6.00E+00	8.00E+00		7.00E+00	[212]	National Calculation Methodology value taken as mean with 1hr band
kitchen equipment off	time	triangular	1.40E+01	1.60E+01		1.50E+01	[212]	National Calculation Methodology value taken as mean with 1hr band
general lighting on	time	triangular	6.00E+00	7.00E+00		6.00E+00		based on partial occupancy times

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
general lighting off	time	triangular	1.70E+01	1.90E+01		1.80E+01		based on partial occupancy times
kitchen lighting on	time	triangular	6.00E+00	8.00E+00		7.00E+00		based on occupancy times
kitchen lighting off	time	triangular	1.40E+01	1.6+01		1.50E+01		based on occupancy times
general heating on	time	triangular	3.00E+00	5.00E+00		4.00E+00	[212]	National Calculation Methodology value taken as mean with 1hr band
general heating off	time	triangular	1.60E+01	1.80E+01		1.70E+00	[212]	National Calculation Methodology value taken as mean with 1hr band
kitchen heating on	time	triangular	6.00E+00	8.00E+00		7.00E+00	[212]	National Calculation Methodology value taken as mean with 1hr band
kitchen heating off	time	triangular	1.30E+01	1.50E+01		1.4E+01	[212]	National Calculation Methodology value taken as mean with 1hr band
ventilation temperature	°C	normal			1.80E+00	2.05E+01	[213]	

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
infiltration rate	ach^{-1}	triangular	3.50E-01	9.00E-01		6.25E-01	[207, table 4.21]	min is average Part L (2002) value and max is peak leaky value
boiler water outlet temperature	°C	uniform	6.00E+01	9.50E+01		7.75E+01		Estimate to test parameter
boiler part load ratio	fraction	uniform	2.00E-01	6.00E-01		4.00E-01		estimate to test parameter
boiler efficiency	%	normal			2.5E-02	7.80E-01	[214]	
dhw design loop exit temp	°C	uniform	5.00E+01	7.00E+01		6.00E+01		estimate to test variable
dhw loop design temp difference	°C	uniform	3.00E+00	7.00E+00		5.00E+00		estimate to test variable
window air gap	m	triangular	6.00E-03	2.00E-02		1.30E-02		estimate to test parameter
glass thermal conductivity	W/mK	triangular	6.04E-01	5.75E+00		1.29E+00	[215, table A18],[207, table 3.23]	Minimum value from MacDonald. Subsequent review identified upper value as unrealistically high, see notes below.

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
insulation urea foam thermal conductivity	W/mK	triangular	3.20E-02	1.80E-01		1.06E-01	[215, table A22], [207]	Minimum value from MacDonald. Subsequent review identified upper value as unrealistically high, see notes below.
cast concrete thermal conductivity	W/mK	triangular	1.14E+00	2.22E+00		1.68E+00	[215, table A15]	Minimum and maximum at ± 1 st.dev
screed thermal conductivity	W/mK	triangular	4.46E-01	1.13E+00		07.87E-01	[215, table A30]	Minimum and maximum at ± 1 st.dev
linoleum thermal conductivity	W/mK	triangular	1.70E-01	3.50E-01		2.60E-01	[216]	Minimum and maximum set to ±50%
asphalt thermal conductivity	W/mK	triangular	7.42E-01	1.36E+00		1.05E+00	[215, table A4]	Minimum and maximum at ± 1 st.dev
fibreboard thermal conductivity	W/mK	triangular	3.00E-02	9.00E-02		6.00E-02	[216]	Minimum and maximum set to ±50%

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
extruded polystyrene thermal conductivity	W/mK	triangular	3.20E-02	7.60E-02		5.40E-02	[215, table A22]	Minimum and maximum at ± 1 st.dev
plasterboard thermal conductivity	W/mK	triangular	4.10E-02	3.41E-01		1.91E-01	[215, table A26]	Minimum and maximum at ± 1 st.dev
brickwork thermal conductivity	W/mK	triangular	5.28E-01	1.05E+00		7.89E-01	[215, table A8]	Minimum and maximum at ± 1 st.dev
blockwork thermal conductivity	W/mK	triangular	6.79E-01	1.17E+00		9.22E-01	[215, table A5]	Minimum and maximum at ± 1 st.dev
plastering thermal conductivity	W/mK	triangular	2.82E-01	7.86E-01		5.34E-01	[215, table A27]	Minimum and maximum at ± 1 st.dev
oak thermal conductivity	W/mK	triangular	1.09E-01	1.93E-01		1.51E-01	[215, table A35]	Minimum and maximum at ± 1 st.dev
Cast concrete lightweight thermal conductivity	W/mK	triangular	1.69E-01	4.57E-01		3.13E-01	[215, table A14]	Minimum and maximum at ± 1 st.dev

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
Cast concrete lightweight thickness	m	triangular	7.50E-02	1.25E-01		0.1000		Minimum and maximum at$\pm$ 1 st.dev
glass thickness	m	triangular	5.00E-03	7.00E-03		6.00E-03		Minimum and maximum at $\pm$25% of default value
insulation urea foam thickness	m	triangular	1.23E-01	1.43E-01		1.33E-01		Minimum and maximum at $\pm$25% of default value
cast concrete thickness	m	triangular	9.00E-02	1.10E-01		1.00E-01		Minimum and maximum at $\pm$25% of default value
screed thickness	m	triangular	6.50E-02	7.50E-02		7.00E-02		Minimum and maximum at $\pm$25% of default value. Default value confirmed with reference to BS 8204-2:2003+A2:2011. Screeds, bases and in situ floorings [217]

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
linoleum thickness	m	triangular	2.50E-02	3.50E-02		3.00E-02		Minimum and maximum at ±25% of default value. Default values subsequently identified as unrealistic in comparison with BS EN 686:2011 - Resilient floor coverings [218]. See notes below for details.
asphalt thickness	m	triangular	1.70E-02	2.10E-02		1.90E-02		Minimum and maximum at ±25% of default value.
fibreboard thickness	m	triangular	1.10E-02	1.50E-02		1.30E-02		Minimum and maximum at ±25% of default value
extruded polystyrene thickness	m	triangular	4.30E-02	5.30E-02		4.80E-02		Minimum and maximum at ±25% of default value
plasterboard thickness	m	triangular	2.30E-02	2.70E-02		2.50E-02		Minimum and maximum at ±25% of default value

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
brickwork thick-ness	m	triangular	9.50E-02	1.03E-01		1.00E-01		Minimum and maximum at ±25% of default value
blockwork thick-ness	m	triangular	9.50E-02	1.03E-01		1.00E-01		Minimum and maximum at ±25% of default value
plastering thick-ness	m	triangular	1.00E-02	2.00E-02		1.50E-02		Minimum and maximum at ±25% of default value
oak thickness	m	triangular	3.00E-02	4.00E-02		3.50E-02		Minimum and maximum at ±25% of default value
metabolic gains general	W	normal	1.15E+02	1.70E+02	2.75E+01	1.42E+02	[215, fig. 4.6]	
metabolic gains corridor	W	normal	2.00E+02	2.25E+02	1.25E+01	2.12E+02	[215, fig. 4.6]	
metabolic gains sport	W	normal	3.25E+02	4.25E+02	5.0E+01	3.75E+02	[215, fig. 4.6]	
Classroom temp controlled purge ventilation rate	ach^{-1}	triangular	1.33E+00	9.27E+00		5.51E+00	[219, table 2]	cases 6 & 7 - purge venti-lation, less base ventilation

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
Classroom continuous base ventilation rate	ach^{-1}	triangular	0.00E+00	4.87E+00		2.43E+00	[219, table 1]	cases 6 & 7
Orientation	deg	uniform	0.00E+00	3.59E+02		1.80E+02		

General Assumptions:

- Plant room and stores are unoccupied
- No equipment assumed in circulation areas
- Hall equipment excluded as very low
- Plant equipment included in HVAC
- No equipment in stores
- no equipment assumed in toilets as hand dryers only possible source
- Catering gas consumption is excluded - Hong suggests a median value of 2.3% for catering gas consumption suggesting that this effect would be small [153]
- Lift electricity consumption is excluded. Hong shows negligible energy consumption due to lift use. This is likely due to very infrequent use of lifts for the transport of building users who are unable to use the stairs
- it is assumed that rooms are well-enough insulated and distant from high temperature radiant heat sources for the difference between air and operative temperatures to be small.
- Where reported standard deviation is greater than 25% of the reported mean, minimum and maximum values have been fixed at $\pm$ 1 standard deviation in order to avoid sampling impossible values.
- No shading is including in modelling. However, orientation is included as a variable. This variable was not found to be one of the most influential and thus further investigation of shading/transmission effects was deemed unnecessary.
- Thermal mass of partitions which are not included due to combining of rooms into zones has been excluded since this would have little impact on annual energy consumption which is the output of interest.

The original ranges modelled for three parameter values were found to be unrealistic on subsequent review: glass thermal conductivity, linoleum thickness and urea foam insulation thermal conductivity. Sensitivity analysis was repeated with revised parameter ranges. This indicated that these parameters remained non-influential. The distributions of annual electricity and gas consumption were compared for three sets of 1000 runs for both primary and secondary school, parameter values were sampled from their distributions if influential or fixed at their base value if non-influential using the procedure detailed in section 5.4.9: set A contained new values for the three corrected parameters, fixed at the base value, set B contained new parameter values, sampled from their distributions and set C contained the original parameter values, fixed at the base value. A 2-sample Kolmogorov-Smirnov test was used to compare the resulting distributions. This confirmed that the differences between the three sets of distributions for each utility and building were not statistically significant and thus that updating these three parameter ranges would not affect the results.

Appendix C

ESCO Interview Materials

The impacts of project scale, scope and risk allocation on financial returns for clients and contractors in Energy Performance Contracts - a stochastic modelling analysis

Pamela Fennell
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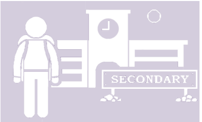
Pamela.fennell.13@ucl.ac.uk

This project is based on 6 case studies which include different numbers of schools, both primary and secondary and different ranges of technologies.

Primary schools



Secondary schools

Boiler replacement

Heating controls

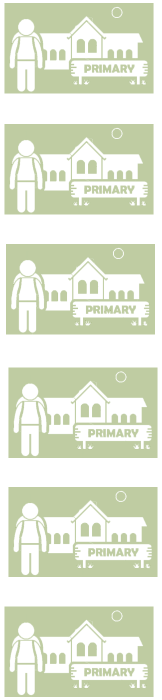
Air tightness seals

Lighting upgrade

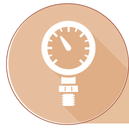
Pipework insulation

Some definitions

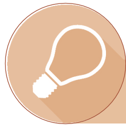
- **Bidding Costs** - the costs which a potential supplier incurs to win a contract. Bidding costs include all the costs which are incurred at risk including any design and survey costs
- **Development Costs** - the costs which are incurred by a supplier after selection by the client. Development costs include finance, legal and administrative costs but exclude design costs
- **Project Management Costs** – the costs of delivering the installation and operational phases
- **Gross Margin** – the excess of revenue from the contact divided by the costs of labour and materials required to perform the contract i.e. excluding overheads



6 Primary schools



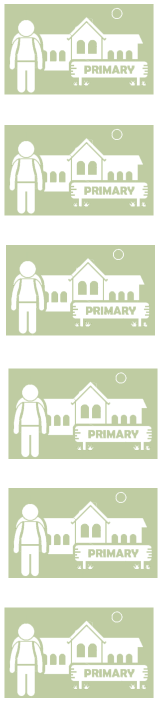
Heating controls



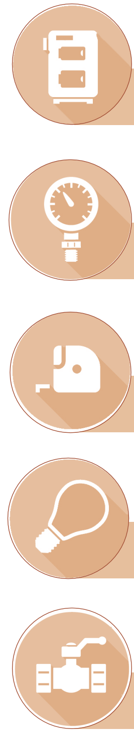
Lighting upgrade

Project A

Bidding	Development	Project Management	Gross Margin



6 Primary schools



Boiler replacement

Heating controls

Air tightness seals

Lighting upgrade

Pipework insulation

Project B

Bidding	Development	Project Management	Gross Margin

10 Primary schools

2 Secondary schools

Heating controls

Lighting upgrade

Project C

Bidding	Development	Project Management	Gross Margin

10 Primary schools

2 Secondary schools

Boiler replacement

Heating controls

Air tightness seals

Lighting upgrade

Pipework insulation

Project D

Heating controls

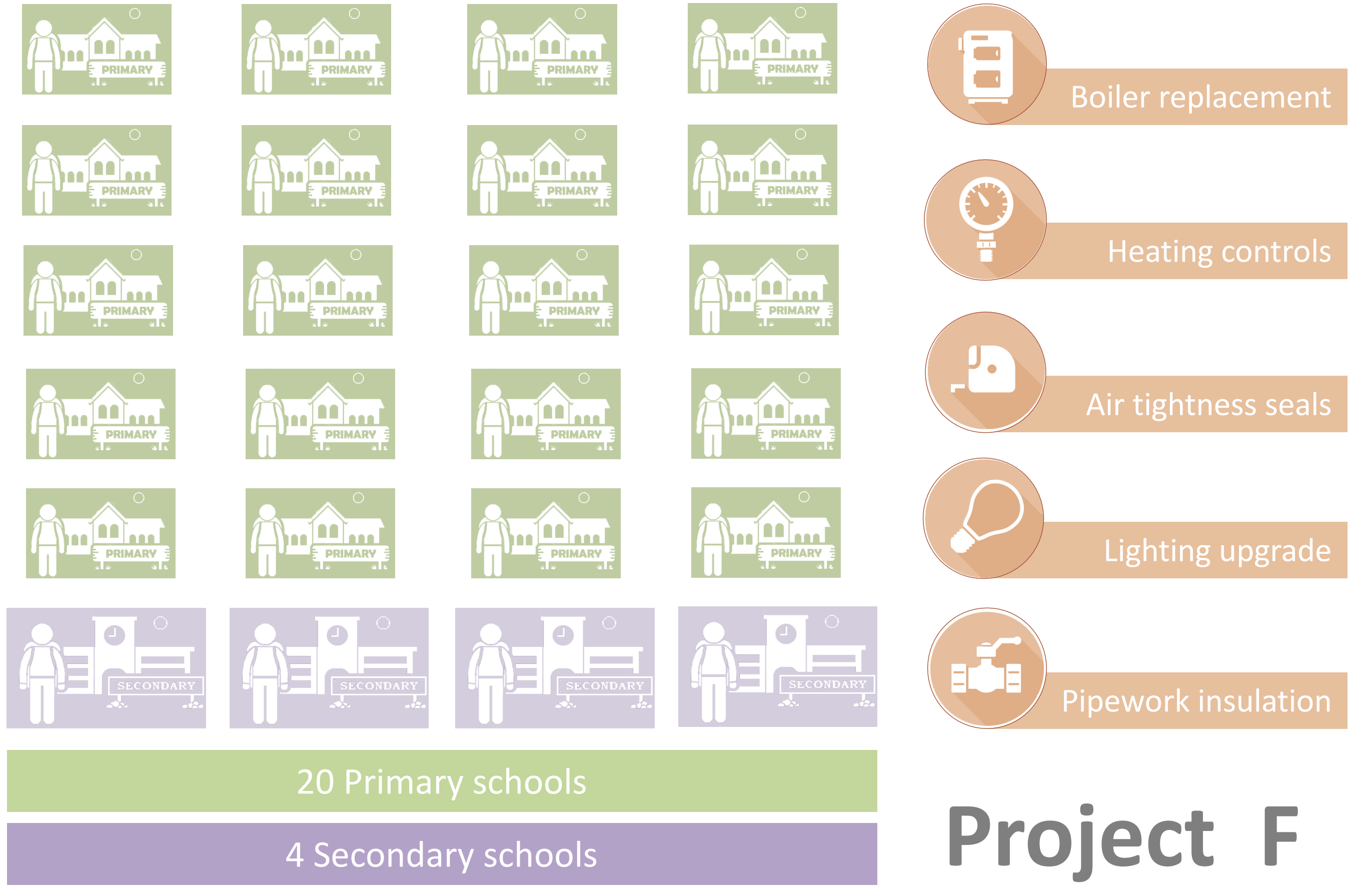
Lighting upgrade

20 Primary schools

4 Secondary schools

Project E

Bidding	Development	Project Management	Gross Margin

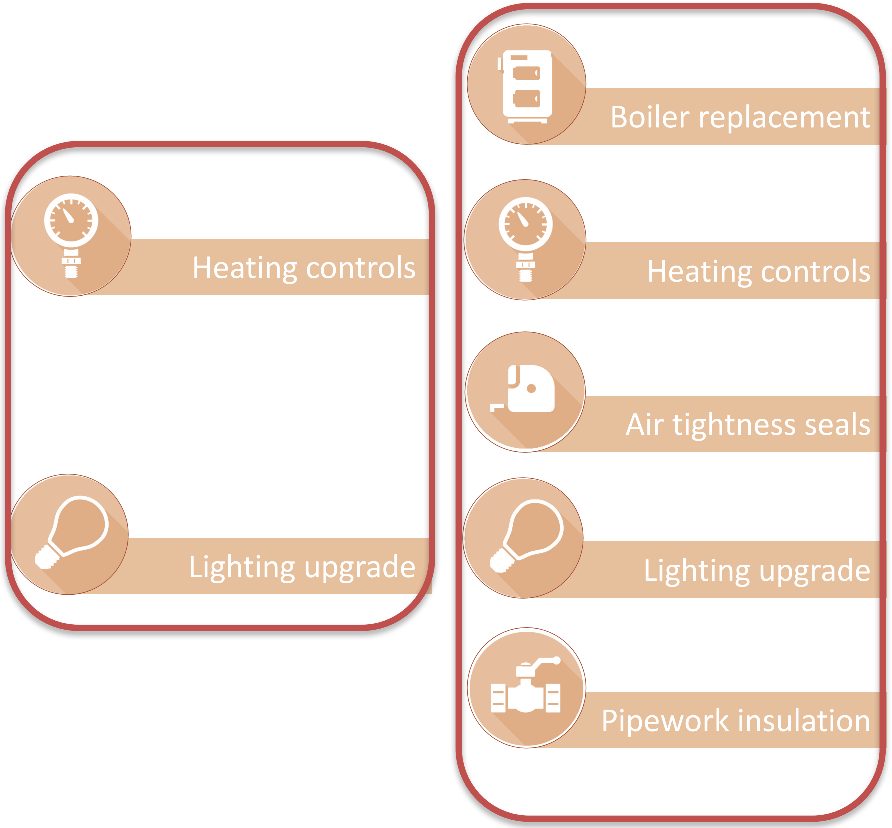


Project F

Bidding	Development	Project Management	Gross Margin

Which measurement and verification strategy do you think would be most appropriate for these 2 groups of technologies?

Change in whole building electricity and gas consumption
Change in metered energy (sub-meters measured over time)
Calibrated computer model
Spot measurements for proof of installation



Appendix D

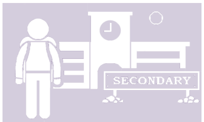
Client Interview Materials

The impacts of project scale, scope and risk allocation on financial returns for clients and contractors in Energy Performance Contracts - a stochastic modelling analysis

Pamela Fennell
Energy Institute
University College London
Pamela.fennell.13@ucl.ac.uk

This project is based on 6 case studies which include different numbers of schools, both primary and secondary and different ranges of technologies.

Primary schools



Secondary schools

Boiler replacement

Heating controls

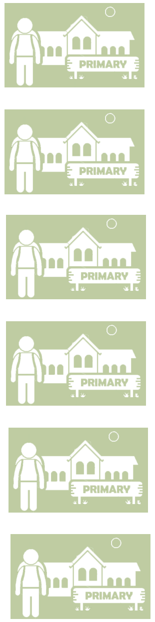
Air tightness seals

Lighting upgrade

Pipework insulation

Some definitions

- **Pre-procurement time** – man-hours preparing documentation for bidders and securing commitment of schools
- **Bid phase time** – man-hours between launch and selection of preferred supplier
- **Installation phase time** – man-hours during the installation phase
- **Guarantee period time** – man-hours during the guarantee period
- **External costs –** fees paid to 3rd parties for support services e.g. lawyers, survey costs, M&V costs



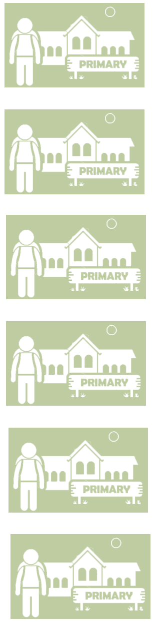
6 Primary schools

Heating controls

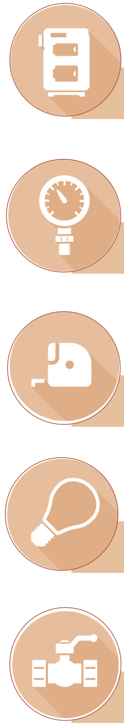
Lighting upgrade

Project A

	Pre-procurement	Bid Phase	Installation	Guarantee Period
Internal time				
External costs				



6 Primary schools



Boiler replacement

Heating controls

Air tightness seals

Lighting upgrade

Pipework insulation

Project B

	Pre-procurement	Bid Phase	Installation	Guarantee Period
Internal time				
External costs				

10 Primary schools

2 Secondary schools

Heating controls

Lighting upgrade

Project C

	Pre-procurement	Bid Phase	Installation	Guarantee Period
Internal time				
External costs				

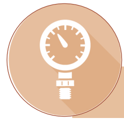
10 Primary schools

2 Secondary schools

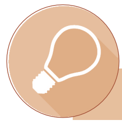
- Boiler replacement
- Heating controls
- Air tightness seals
- Lighting upgrade
- Pipework insulation

Project D

	Pre-procurement	Bid Phase	Installation	Guarantee Period
Internal time				
External costs				



Heating controls



Lighting upgrade

20 Primary schools

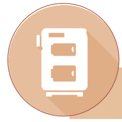
4 Secondary schools

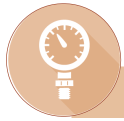
Project E

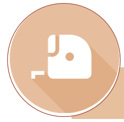
	Pre-procurement	Bid Phase	Installation	Guarantee Period
Internal time				
External costs				

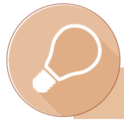
20 Primary schools

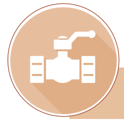
4 Secondary schools


Boiler replacement


Heating controls


Air tightness seals


Lighting upgrade

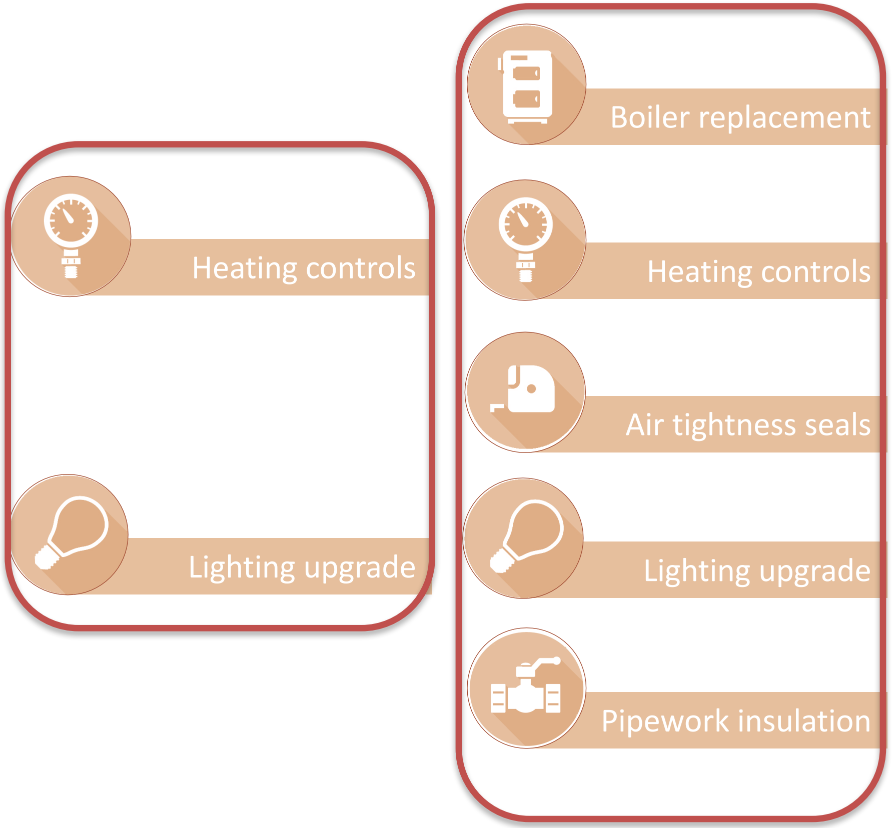

Pipework insulation

Project F

	Pre-procurement	Bid Phase	Installation	Guarantee Period
Internal time				
External costs				

Which measurement and verification strategy do you think would be most appropriate for these 2 groups of technologies?

Change in whole building electricity and gas consumption
Change in metered energy (sub-meters measured over time)
Calibrated computer model
Spot measurements for proof of installation



Appendix E

Parameter Values and Ranges Post-Intervention

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
classroom lighting levels	W/m^2	triangular	4.28	4.52		4.40	[220, table 3]	
office lighting levels	W/m^2	triangular	5.25	5.55		5.40	[220, table 3]	
hall lighting levels	W/m^2	triangular	5.54	5.86		5.70	[220, table 3]	
ancillary lighting levels	W/m^2	triangular	3.01	3.19		3.10	[220, table 3]	
intermittent heating set point	^oC	triangular	19.00	21.00		20.00	[221]	
regular heating set point	^oC	triangular	19.00	21.00		20.00	[221]	
general lighting on	time	triangular	5.00	7.00		6.00		tied to occupancy variable
general lighting off	time	triangular	17.00	19.00		18.00		tied to occupancy variable
kitchen lighting on	time	triangular	6.00	8.00		7.00		tied to occupancy variable
kitchen lighting off	time	triangular	14.00	16.00		15.00		tied to occupancy variable

Variable	**Units**	**Distribution**	**min**	**max**	σ	μ	**Source**	**Notes**
general heating on	time	triangular	5.00	7.00		6.00		tied to occupancy variable
general heating off	time	triangular	17.00	19.00		18.00		tied to occupancy variable
kitchen heating on	time	triangular	6.00	8.00		7.00		tied to occupancy variable
kitchen heating off	time	triangular	14.00	16.00		15.00		tied to occupancy variable
infiltration rate	ach^{-1}	triangular	3.50E-01	7.00E-01		5.25E-01	[207, table 4.21]	min is average Part L (2002) value and max is peak leaky value
boiler part load ratio	fraction	uniform	1.90E-01	2.70E-01		1.00E-01		[222]
boiler efficiency	%	normal			1.1E-02	9.40E-01	[63]	

Appendix F

ECM Installation Costs

Permission to reproduce this report has been granted by Currie & Brown UK Limited

UCL

Costs of energy conservation measures in school buildings

Report (updated)

24 March 2017

Currie & Brown

Contents

1. Introduction

This short report summarises analysis to support research on the commercial viability of EPC projects. A range of costs has been provided for the installation of energy conservation measures into a theoretical primary and secondary school using an energy performance contract.

The scenarios are based on two buildings modelled by UCL. The energy conservation measures costed are:

- Valve and Flange Insulation- New thermal jackets and pipe insulation
- BMS Upgrade - New sensors, recalibration of set points and operating hours
- Boiler replacement - New modulating condensing gas boilers
- Fabric Improvements - Sealing of junction of walls and roof, sealing around windows, sealing of extracts
- BMS replacement - Basic BMS installed with lighting and heating controls
- Lighting Upgrade
  - Option 1 – Lamp replacement - T8 fluorescent lamps replaced with T8 LED lamps and HF electronic ballasts
  - Option 2 – Luminaire replacement Luminaires and 58W T8 fluorescent lamps replaced with T8 LED lamps and HF electronic ballasts

The costs provided in this report are drawn from between 3 and 12 contractor quotes for similar work and also Currie & Brown's own cost consulting teams who maintain benchmark prices for fabric, HVAC and other building costs.

2. Primary School

The theoretical primary school modelled is a 1970's two storey building with a total area of 2,134m^2. The Tables 2.1 and 2.2 and the graphs in Figure 2.1 show the estimated cost ranges for each modelled energy conservation measure inclusive of purchase, installation, strip out of existing and preliminaries.

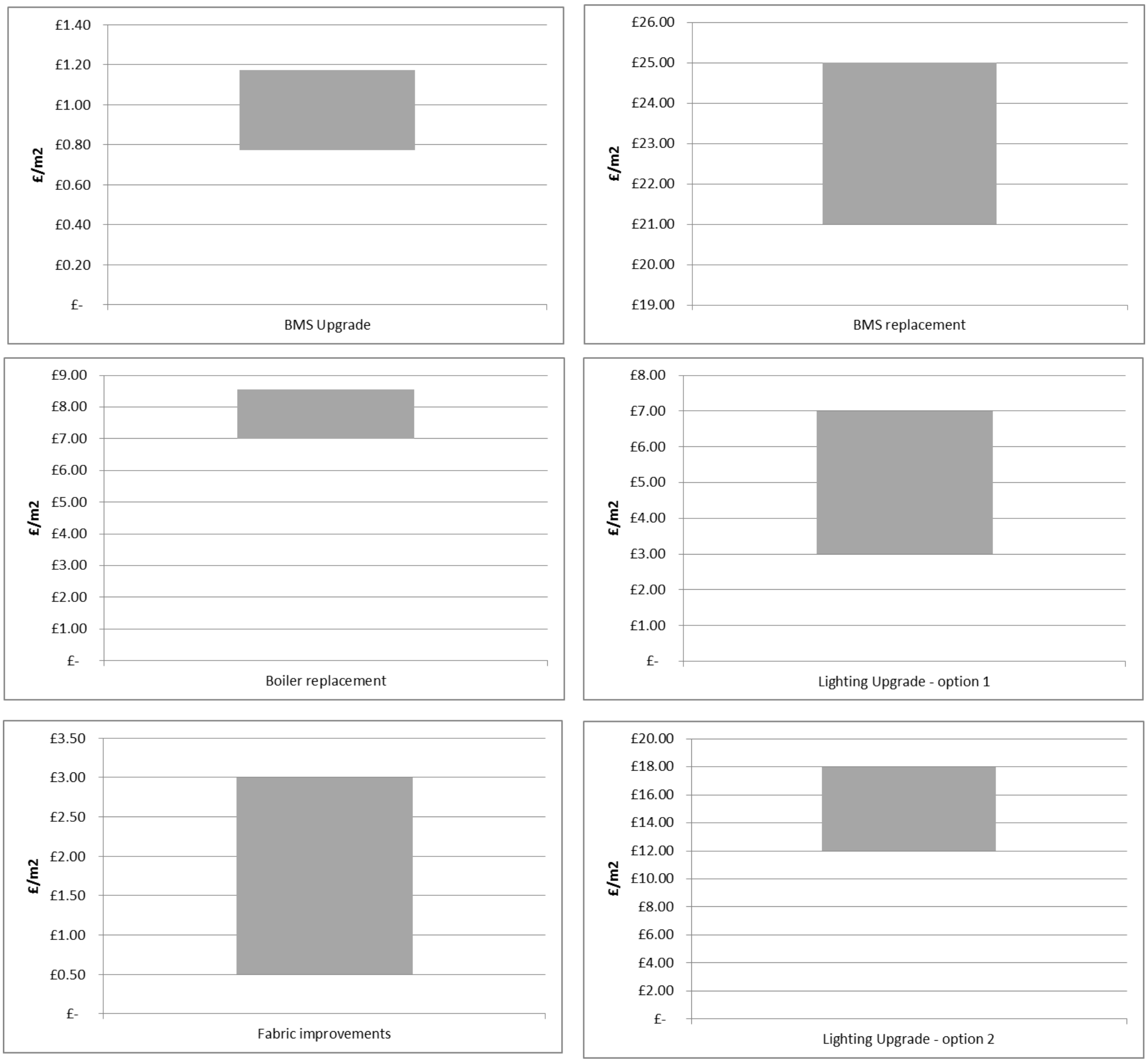
Table 2.1 Cost of various ECM's per m^2 for a primary school

	ECM Cost (£/m2)		
	Low	Med	High
BMS Upgrade	£ 0.77	£ 0.94	£ 1.17
Boiler replacement (2*80kW)	£ 7.17	£ 7.97	£ 8.76
Fabric improvements	£ 0.50	£ 1.50	£ 3.00
BMS replacement	£ 21.00	£ 23.00	£ 25.00
Lighting Upgrade - option 1	£ 3.00	£ 5.00	£ 7.00
Lighting Upgrade - option 2	£ 12.00	£ 15.00	£ 18.00

Table 2.2 Cost of various ECM's for a primary school

	ECM Cost (£ total)		
	Low	Med	High
BMS Upgrade	£1,650	£2,000	£2,500
Boiler replacement (2*80kW)	£15,300	£17,000	£18,700
Fabric improvements	£1,100	£3,200	£6,400
BMS replacement	£44,800	£49,100	£53,350
Lighting Upgrade - option 1	£6,400	£10,700	£14,950
Lighting Upgrade - option 2	£25,600	£32,000	£38,400

Figure 2.1 Graphs of cost range for each ECM for a primary school



3. Secondary School

The theoretical secondary school modelled is a 1970's two storey building with a total area of 8,411m^2. The Tables 3.1 and 3.2 and the graphs in Figure 3.1 show the estimated cost ranges for each modelled energy conservation measure inclusive of purchase, installation, strip out of existing and preliminaries.

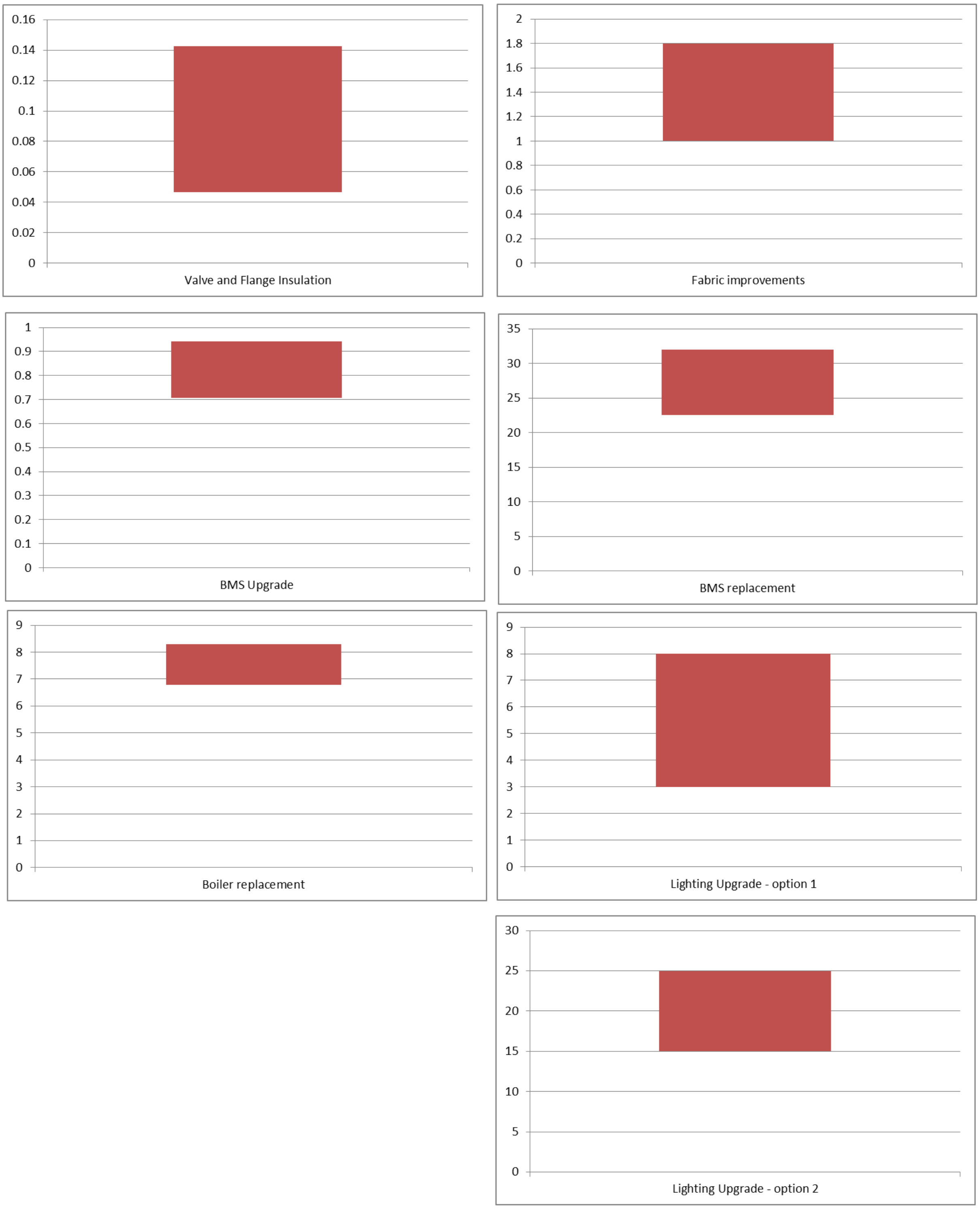
Table 3.1 Cost of various ECM's per m^2 for a secondary school

	ECM Cost (£/m2)		
	Low	Med	High
Valve and Flange Insulation	£ 0.06	£ 0.11	£ 0.14
BMS Upgrade	£ 0.77	£ 0.94	£ 1.17
Boiler replacement	£ 6.80	£ 7.50	£ 8.30
Fabric improvements	£ 0.50	£ 1.50	£ 3.00
BMS replacement	£ 21.00	£ 23.00	£ 25.00
Lighting Upgrade - option 1	£ 3.00	£ 5.00	£ 7.00
Lighting Upgrade - option 2	£ 12.00	£ 15.00	£ 18.00

Table 3.2 Cost of various ECM's for a secondary school

	ECM Cost (£ total)		
	Low	Med	High
Valve and Flange Insulation	£500	£950	£1,200
BMS Upgrade	£6,503	£7,883	£9,854
Boiler replacement	£57,150	£63,500	£69,850
Fabric improvements	£4,206	£12,617	£25,233
BMS replacement	£176,631	£193,453	£210,275
Lighting Upgrade - option 1	£25,233	£42,055	£58,877
Lighting Upgrade - option 2	£113,549	£126,165	£151,398

Figure 3.1 Graphs of cost range for each ECM - secondary school



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Appendix G

ESCO M&V Responses

This appendix contains confidential information which is not for publication. This content is included for examiners only.

Appendix H

DSCF Parameter Values and Ranges

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
Fixed Inputs								
Salix loan term	years					8	[125]	
Discount rate	%					3.5	section 4.7.2	
Stochastic Inputs - Common								
Guarantee buffer	%	uniform	0	10		5		section 4.7.3
Inflation index	%	uniform	1.5	2.5		2		table 4.5.1
Loan rate	%	uniform	1.5	2.5		2	[126]	
Primary school installation costs - ECM set 1	£	uniform	27,300	40,900		34,000	appendix F	
Secondary school installation costs - ECM set 1	£	uniform	120,100	161,300		143,000	appendix F	
Primary school installation costs - ECM set 2	£	uniform	43,700	66,000		54,200	appendix F	

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
Secondary school installation costs – ECM set 2	£	uniform	181,900	257,600		211,100	appendix F	
Stochastic Inputs – Project A								
Client transaction costs	£	triangular	53,400	83,000		67,400	section 6.2.2	
ESCO transaction costs	£	triangular	28,900	69,100		39,300	section 6.2.1	
Client project management costs	£	triangular	18,000	35,500		25,200	section 6.2.2	
ESCO Margin	%	uniform	6	25		13	section 6.2.1	
Stochastic Inputs – Project B								
Client transaction costs	£	triangular	53,400	83,000		67,400	section 6.2.2	
ESCO transaction costs	£	triangular	34,000	92,300		49,100	section 6.2.1	
Client project management costs	£	triangular	18,000	33,600		25,200	section 6.2.2	

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
ESCO Margin	%	uniform	5	25		13	section 6.2.1	
Stochastic Inputs - Project C								
Client transaction costs	£	triangular	66,600	84,500		75,100	section 6.2.2	
ESCO transaction costs	£	triangular	61,500	220,200		115,700	section 6.2.1	
Client project management costs	£	triangular	27,000	40,200		33,300	section 6.2.2	
ESCO Margin	%	uniform	6	25		14	section 6.2.1	
Stochastic Inputs - Project D								
Client transaction costs	£	triangular	66,600	84,500		75,100	section 6.2.2	
ESCO transaction costs	£	triangular	72,000	296,400		143,000	section 6.2.1	
Client project management costs	£	triangular	27,000	40,200		33,300	section 6.2.2	
ESCO Margin	%	uniform	5	20		14	section 6.2.1	
Stochastic Inputs - Project E								

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
Client transaction costs	£	triangular	66,000	93,000		79,300	section 6.2.2	
ESCO transaction costs	£	triangular	92,300	462,000		232,000	ection 6.2.1	
Client project management costs	£	triangular	27,000	53,700		39,300	section 6.2.2	
ESCO Margin	%	uniform	6	20		13	section 6.2.1	
Stochastic Inputs - Project F								
Client transaction costs	£	triangular	66,600	93,000		79,300	section 6.2.2	
ESCO transaction costs	£	triangular	150,900	620,000		252,900	section 6.2.1	
Client project management costs	£	triangular	27,000	53,700		39,300	section 6.2.2	
ESCO Margin	%	uniform	5	20		16	section 6.2.1	
Energy Savings - ECM set 1								

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
Expected annual electricity saving – primary school	J					1.56E11		Calculated
Expected annual gas saving – primary school	J					3.79E10		Calculated
Expected annual electricity saving – secondary school	J					5.79E11		Calculated
Expected annual gas saving – secondary school	J					4.02E10		Calculated
Option A annual electricity saving – primary school	J					1.56E11		calculated
Option B annual electricity saving – primary school	J		8.03E10	2.64E11	3.28E10	1.56E11		summary statistics for EnergyPlus models

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
Option C annual electricity saving – primary school	J		8.04E10	2.64E11	3.28E10	1.66E11		summary statistics for EnergyPlus models
Option A annual gas saving – primary school	J					3.79E10		calculated
Option B annual gas saving – primary school	J					3.79E10		calculated
Option C annual gas saving – primary school	J		-1.27E12	1.65E12	3.98E11	5.45E10		summary statistics for EnergyPlus models
Option A annual electricity saving – secondary school	J					5.79E11		calculated
Option B annual electricity saving – secondary school	J		2.61E11	7.12E11	8.46E10	4.61E11		summary statistics for EnergyPlus models

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
Option C annual electricity saving - secondary school	J		2.61E11	8.48E11	9.45E10	5.52E11		summary statistics for EnergyPlus models
Option A annual gas saving - secondary school	J					4.02E11		calculated
Option B annual gas saving - secondary school	J					4.02E11		calculated
Option C annual gas saving - secondary school	J		-4.97E12	5.89E12	1.55E12	4.74E11		summary statistics for EnergyPlus models
Energy Savings - ECM set 2								
Expected annual electricity saving - primary school	J					1.56E11		Calculated

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
Expected annual gas saving – primary school	J					1.37E11		Calculated
Expected annual electricity saving – secondary school	J					5.79E11		Calculated
Expected annual gas saving – secondary school	J					1.45E12		Calculated
Option A annual electricity saving – primary school	J					1.56E11		calculated
Option B annual electricity saving – primary school	J		8.49E10	2.73E11	3.18E10	1.66E11		summary statistics for EnergyPlus models
Option C annual electricity saving – primary school	J		8.46E10	2.73E11	3.18E10	1.66E11		summary statistics for EnergyPlus models

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
Option A annual gas saving - primary school	J					1.37E11		calculated
Option B annual gas saving - primary school	J		-5.43E11	1.60E12	3.08E11	2.69E11		summary statistics for EnergyPlus models
Option C annual gas saving - primary school	J		-4.95E11E12	2.00E12	3.92E11	4.92E11		summary statistics for EnergyPlus models
Option A annual electricity saving - secondary school	J					5.79E11		calculated
Option B annual electricity saving - secondary school	J		2.32E11	7.89E11	8.65E10	4.86E11		summary statistics for EnergyPlus models
Option C annual electricity saving - secondary school	J		2.61E11	9.07E11	9.58E10	5.74E11		summary statistics for EnergyPlus models

Variable	Units	Distribution	min	max	σ	μ	Source	Notes
Option A annual gas saving - secondary school	J					1.45E12		calculated
Option B annual gas saving - secondary school	J		-2.82E12	5.89E12	1.19E12	1.25E12		summary statistics for EnergyPlus models
Option C annual gas saving - secondary school	J		-2.55E12	7.63E12	1.50E12	2.23E12		summary statistics for EnergyPlus models

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